Center for Applied Environmental Law and Policy

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Technical Review of:

Gasoline Engine Technologies for Revised 2023 and Later Model Year Light – Duty Vehicle Greenhouse Gas Emission Standards

Final Report

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Center for Applied Environmental Law and Policy

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CAELP Gasoline Engine Technologies for Improved Efficiency			
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Revision Summary

Date	Version	Change Description
03/10/2021	1.0	Preliminary release
05/11/2021	2.0	Release incorporating CAELP feedback and comments
06/08/2021	3.0	Draft release v1
06/18/2021	4.0	Draft Release v2
09/10/2021	5.0	Release incorporating EPA feedback and comments
09/17/2021	6.0	Release incorporating EPA, CAELP feedback and comments

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Glossary

BEV	-	Battery Electric Vehicle
BISG	-	Belt Integrated Starter Generator
BMEP	-	Brake Mean Effective Pressure
BNEF	-	Bloomberg New Energy Finance
BSFC	-	Brake Specific Fuel Consumption
BSR	-	Bore to Stroke Ratio
BTE	-	Brake Thermal Efficiency
CAFE	-	Corporate Average Fuel Economy
CO	-	Carbon Monoxide
CISG	-	Crank Integrated Starter Generator
COV	-	Coefficient of Variation
CR	-	Compression Ratio
CVT	-	Continuously Variable Transmission
Deac	-	Deactivation (Cylinder Deactivation)
DEGR	-	Dedicated Exhaust Gas Recirculation
DOHC	-	Double Over Head Cam
DI	-	Direct Injection
DSF	-	(Tula Technologies) Dynamic Skip Fire. Technology also referred to as Advanced Deac (Cylinder Deactivation)
EGR	-	Exhaust Gas Recirculation
EIVC	-	Early Intake Valve Closing
EPA	-	Environmental Protection Agency
EU	-	European Union
FCEV	-	Fuel Cell Electric Vehicle
GBDI	-	Groundless Barrier Discharge Igniter

GHG - Green House Gas

HCCI - Homogeneous Charge Compression Ignition

HEV - Hybrid Electric Vehicle

HVAC - Heating Ventilation and Air Conditioning

IMEP - Indicated Mean Effective Pressure

IC - Internal Combustion

ISG - Integrated Starter Generator

LCOE - Levelized Cost of Electricity

LIVC - Late Intake Valve Closing

LTC - Low-Temperature Combustion

MBF - Mass Burned Fraction

NA - Naturally Aspirated

NHTSA - National Highway Traffic Safety Administration

NMOG - Non-Methane Organic Gases

NOx - Nitrogen Oxides

NVH - Noise Vibration Harshness

NVO - Negative Valve Overlap (Exhaust valve closes before the gas exchange TDC and the intake valve opens after the gas exchange TDC)

OE/OEM - Original Equipment / Original Equipment Manufacturer

OPE - Opposed Piston Engine

PCCI - Partially Premixed Compression Ignition

PFI - Port Fuel Injection

PHEV - Plugin Hybrid Electric Vehicle

PV - Pressure-Volume

RCCI - Reactivity Controlled Compression Ignition

SACI - Spark Controlled Compression Ignition

SCR	-	Selective Catalyst Reduction
SPCCI	-	Spark Plug Controlled Compression Ignition
SUV	-	Sports Utility Vehicle
TDC	-	Top Dead Center
TKE	-	Turbulent Kinetic Energy
TWC	-	Three-Way-Catalyst
VCR	-	Variable Compression Ratio
VGT	-	Variable Geometry Turbocharger (VGT)
VCT	-	Variable Cam Timing
VVT	-	Variable Valve Timing
YOY	-	Year on Year

Executive Summary

Roush Industries was commissioned by CAELP to assess the current state-of-the-art in gasoline-fueled light-duty engines and powertrains and recommend both near and longer-term areas of focus for continued reduction in greenhouse gas emissions associated with improvements in effective fuel economy. This effort included both a review of ongoing R&D activities by automakers, suppliers, engineering development companies, research institutes, and governmental agencies and internal Roush modeling and development experience.

Recommended Near-term Areas of Focus (2025)

Naturally Aspirated Engines: Based on a review of published data, information from major automotive suppliers, and proprietary knowledge of potential product plans, Roush recommends that EPA focus on Atkinson cycle engines with higher geometric compression ratio, lower bore-to-stroke ratios, and increased cooled EGR dilution. For consistent ignition and acceptable burn rates these engines should have some combination of a) Intake, cylinder head, and piston design improvements for high in-cylinder turbulence; b) High energy ignition systems such as high energy spark plugs, plasma ignition, prechamber ignition, etc.; and c) In-cylinder fuel reforming technologies such as Direct EGR or pilot fuel injection during negative valve overlap.

Turbocharged Engines: Future turbocharged engines should contain increased use of the Miller cycle with a smaller bore to stroke ratio, higher geometric compression ratio (with higher Miller ratios), and higher EGR dilution rates. Therefore, Roush recommends that EPA focus on Miller cycle engines with advanced boosting technologies such as variable geometry turbochargers, electrically assisted turbochargers, or a combination of a turbocharger and an electric supercharger. Similar to naturally aspirated engines, for consistent ignition and acceptable burn rates EPA should focus on future turbocharged engines which contain combinations of a) Intake, cylinder head, and piston design elements for high in-cylinder turbulence; b) High energy ignition systems such as high energy spark plugs, plasma ignition, passive prechamber ignition, etc.; and c) In-cylinder fuel reforming technologies such as Direct EGR or pilot fuel injection during negative valve overlap

Mild Hybrid: Suppliers are developing 48-volt systems with higher power outputs (20 - 30kW). EPA should focus on the integration of such higher power 48-volt mild hybrid systems to evaluate potential advancements in launch assist, low-speed electric driving, aggressive fuel cutoff, start-stop, and torque assist during driver tip-in. In addition, these higher power ISG systems should be applied to demonstrate further advancements in synergistic technologies such as advanced electric boosting solutions, high energy ignition systems, advanced cylinder deactivation (dampen torsional vibrations), electric accessories (HVAC compressor), and an electrically heated catalyst. The use of heated catalysts will enable fuel economy to be optimized without concern of low catalyst temperatures which may result from aggressive start-stop strategies. Applications of the 48V motor-generator capability should be evaluated in P2, P3, or P4 configurations, opposed to the current P0 geometries.

Full Hybrid Powertrains: The torque provided by the electric motor partially decouples engine output from the driver pedal. This effectively makes the hybrid system an energy management tool that can optimize engine speed-load demands to maximize the time spent in the high-efficiency parts of the engine operating map. Accordingly, low load engine operation is minimized by using the electric drive. EPA should focus on the expanded application of energy management capabilities in full hybrid powertrains to also minimize operation under the low-speed high torque areas of the engine which are prone to knocking by torque augmentation with the electric motor. The instantaneous torque capability of the electric motor can effectively support transient torque demand. This will allow both naturally aspirated and turbocharged engines that are part of a hybrid powertrain to be optimized for a narrow operating range incorporating higher compression ratios and increased EGR dilution (maintaining stoichiometric operation), thereby prioritizing efficiency over peak torque at low engine speeds and transient response, while maintaining good drivability.

Recommended Longer-Term Areas of Focus (2030): In the long term, Roush anticipates that continued pressure on improved thermal efficiency will cause engines to migrate almost exclusively to very lean, air-diluted mixtures, which will also require advanced turbocharging to maintain acceptable power levels.

EPA should focus on expanded capabilities of turbocharged, low bore-to-stroke ratio Miller-cycle engines with some form of electrified boosting solution (turbocharger + 48V supercharger or a 48V electrically assisted turbocharger) that offers precise air path control for high air dilution and improved transient performance. The average 48V motor-generator will likely have a much higher power output 30 kW or more) in a P2, P3, or P4 configuration with increasing hybrid capabilities. The 48V motor will smooth out torsional vibrations which result from aggressive (advanced) cylinder deactivation system strategies. Full hybrid powertrains will enable the turbocharged engines to be highly optimized for a narrow operating range and have a much higher compression ratio and brake thermal efficiencies.

EPA should also focus on high air dilution engines with high-energy ignition systems that enable homogeneous lean operation (lambda>2.0) where engine-out NOx is below the threshold requiring any NOx aftertreatment system. Such engines will have brake thermal efficiency approaching 50%.

Recommended Future Areas of Focus (2035 and beyond):

Increasingly stringent worldwide environmental regulatory pressure, coupled with accelerating progress in battery and electric motor performance and cost reduction, has caused significant OEM investment and a major shift in product development toward battery electric vehicles. Therefore, in the absence of geopolitical market manipulation of key raw material availability and cost, Roush believes new product introduction in light-duty vehicles will be dominated by battery electric vehicles in 2035 and beyond. This conclusion is based on the following factors:

- The projected cost trajectory of the battery, power electronics, and traction motors from 2020 to 2030.
- New battery technologies in pilot production have shown significant improvements in cost, cycle life, and energy density.

- Advancements in pack construction and automation resulting in cost and weight savings
- Improvements in the energy efficiency (lower energy losses) of EVs making it feasible to use lower-cost battery chemistries (Lithium Iron Phosphate) for small and midsize vehicles with a range of 200 miles, or more.
- Modularity and economies of scale of EV powertrain components – The ability to share components across different manufacturers, vehicles, etc. at a scale not possible with IC engines
- The projected electric energy generation capacity to be added from 2020 to 2035 for fleet electrification and the falling Levelized Cost of Electricity (LCOE) of renewables + grid storage which is already below other conventional forms of energy generation (Coal, Natural gas, Nuclear, etc.).
- Advancements in lower-cost stationary power storage that is essential as a buffer between the grid and high-power charging stations.

However, other factors may play a role, and the continued sale of IC engine-powered vehicles at some level is possible. For example, for heavier vehicles like full-size trucks and SUVs, advancements in carbon-neutral fuels could result in some continued sales of internal combustion powertrains. Any future use of internal combustion engines in light-duty vehicles beyond 2035 will be limited to being part of an electrified (hybrid) powertrain. To the extent used, they will most likely be turbocharged lean-burn Miller-cycle engines with a brake thermal efficiency of about 50%.

Project Recommendations:

Based on an assessment of the state-of-the-art and future developments in light- and medium-duty combustion engines, several projects are recommended which benchmark early production introduction of innovative technologies or assess combinations of advanced technologies to demonstrate future potential improvements in greenhouse gas performance and fuel economy.

<u>Future Pickup /Full-Size SUV GHG Reduction</u>

Two powertrain configurations are recommended for study and could support future rulemaking. The first option synergistically combines available technologies (without a major redesign of the underlying engine architecture) to give maximum fuel economy benefit for a relatively low cost, hence high effectiveness. It combines a naturally aspirated DI engine with advanced cylinder deactivation and a 30kW 48V P2 mild hybrid system. The 48V hybrid system is used to actively smooth out crankshaft torque pulsations to enable aggressive cylinder deactivation strategies (advanced deac – like the Tula Skipfire System). Such a system will also enable start-stop, electric creep, regen braking, slow-speed electric driving, and a heated catalyst. Depending on system integration factors Roush estimates a reduction in GHG emissions of 20% or more, compared to a baseline naturally aspirated direct-injection V8.

A future powertrain configuration is also suggested to assess the limits of SI engine-based hybrid systems when combining promising future technologies that have been demonstrated in prototype multicylinder engines. A turbocharged low bore-to-stroke ratio Miller-cycle engine with an electrically assisted turbocharger and active prechamber ignition system operating at $\lambda>2$ would represent an even greater reduction in GHG emissions. It is anticipated that such a future system could reduce GHG emissions by 30-40% when compared to the baseline V8 DI NA engine. For maximum benefit, such an engine could be combined with a high voltage hybrid system to optimize powertrain energy management and limit engine operation to a narrow speed load range.

Compact SUV GHG Reduction

The compact SUV is one of the largest segments in the US market. A 30kW 48-volt P2 system mated to a low bore-to-stroke ratio miller cycle engine with electrified boosting, advanced cylinder deactivation, cooled EGR and a heated catalyst can provide a fuel economy benefit close to a full high voltage hybrid powertrain at a much lower cost. The 48V electric motor can supplement the engine torque under low-speed high load conditions, thereby avoiding this knock-prone area of the engine map. Also, the use of an advanced boosting system, combining a turbocharger and a 48V electric supercharger, will reduce engine backpressure (larger turbine) and improve scavenging, reduce combustion residuals, and reduce the propensity for knock. This combination enables the use of a higher compression ratio, thereby increasing engine efficiency. A combination of a high-energy ignition system (high energy spark plug/ plasma ignition) and fuel reforming by pilot fuel injection during NVO can be used to increase cEGR tolerance at low loads.

The initial part of such a project should include engine and combustion modeling, followed by prototype engine testing. The overall GHG reduction potential will require modeling and optimization of engine design, calibration parameters, and boosting system sizing and control. Roush estimates a reduction in GHG emissions exceeding 30% is possible compared to a level 1 (NHTSA) turbocharged engine.

Effect of Negative Valve Overlap (NVO) fuel reforming on EGR tolerance on an engine

In-cylinder fuel reforming by using pilot fuel injection during NVO has shown to significantly improve cooled EGR (cEGR) tolerance, combustion stability, and engine efficiency. Such a system can have wide application in turbocharged and NA engines across different vehicle segments with minimal hardware requirements. Depending on the base engine, Roush estimates an efficiency improvement, and the corresponding reduction in GHG emissions, in the range of 5 to 10% is possible and low cost, therefore correspondingly high effectiveness.

Benchmarking a production passive prechamber engine for knock resistance and EGR tolerance

Prechamber combustion systems are one of the most promising technologies for improving the dilution limit of engines, thereby improving system efficiency. It can also enable extremely fast burn rates increasing the knock tolerance of turbocharged engines, allowing higher compression ratios and the associated efficiency improvements.

The Maserati Nettuno engine in the 2021 Maserati MC20 will be the first application of a passive prechamber engine in production. However, the primary objective in the MC20 is high performance. It would be very valuable to study the effect of the system on knock tolerance, burn rates, dilution tolerance

(EGR and air), and emissions. The effort should focus on quantifying possible efficiency gains in a non-performance application.

Evaluation of production-intent high energy ignition systems

High energy volume ignition systems can enable combustion of dilute (cEGR or air diluted) in-cylinder mixtures resulting in a step-change in engine efficiency compared to conventional spark plugs. Such systems can be a drop-in replacement for a spark plug, thereby representing a cost-effective GHG improvement option. Such systems should be evaluated for maximum efficiency potential, in conventional, 48V mild hybrid, and full HV hybrid applications.

Roush estimates that systems such as plasma ignition can support good combustion stability with high amounts of cooled EGR, thereby achieving engine efficiency improvements in the range of 5-10% over a baseline turbocharged DI, dual VVT engine. Microwave ignition systems, on the other hand, have the potential to achieve levels consistent with prechamber ignition systems. This would enable lean-burn engines with low engine-out NOx emissions which can achieve brake thermal efficiency which exceeds 45% in light-duty vehicle applications, compared to a level of 36-38% for a baseline turbocharged DI, dual VVT engine.

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1.0 Introduction

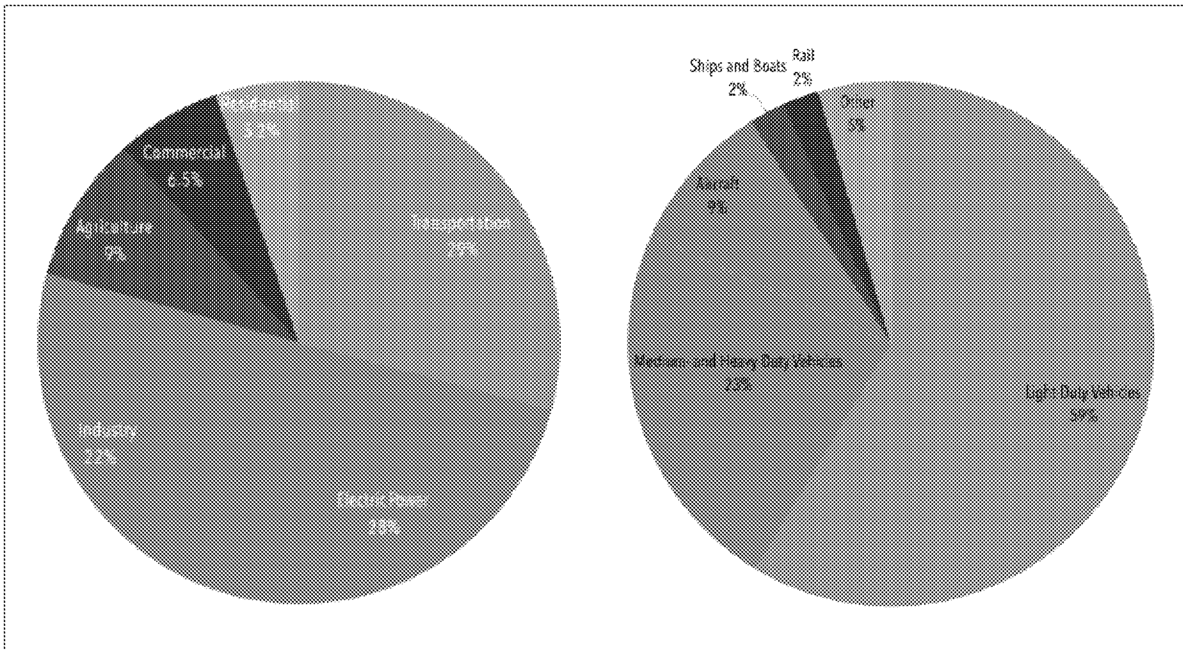


Figure 1: US CO2 emissions by sector and Transportation Sector Emissions [86]

The US light-duty fleet accounts for 59% of the CO2 emissions from the transportation sector. In the long term, a combination of battery electric vehicles and renewable energy to power them will lead to a significant reduction of this CO2 footprint. In the interim, regulatory standards that encourage the introduction of technologies that improve vehicle fuel economy can significantly reduce light-duty CO2 emissions. The future powertrain mix to meet the greenhouse gas and fuel economy standards will likely be a combination of Naturally Aspirated (NA) and downsized boosted (turbocharged/supercharged) gasoline engines, diesel engines, hybrid (HEV), plugin hybrid (PHEV), and battery electric (BEV).

Table 1: Q1 2021 electrified vehicle sales, Source Cox Automotive [90]

	Q1 2021	Q1 2020	Y-O-Y Increase
EVs	98,832	68,247	44.8%
HEVs / PHEVs	204,921	99,719	105.5%
Total Electrified	303,753	167,966	80.8%
Total Market	3,907,738	3,509,299	11.4%
Market share of BEVs	2.53%	1.94%	30.0%
Market share of electrified vehicles	7.77%	4.79%	62.40%

The US BEV market share in 2020 was 1.8% and projected to hit 3.5% in 2021 and 10% in 2025 according to IHS Markit and Bloomberg New Energy Finance (BNEF) [88,89]. The market share of BEVs in Q1 2021 was 2.5% an increase of 45% YOY (table 1) and that of electrified vehicles (BEVs, PHEVs, and HEV) was 7.8% in Q1 2021, an increase of 62% YOY. Based on the data, it can be concluded that the market share of HEVs, PHEVs, and BEVs in 2025 will be significantly higher than 3, 2, and 2% respectively that the EPA and NHTSA assumed in their 2020 SAFE2 Regulatory Impact Analysis [87].

Despite projected increased BEV adoption, a significant portion of vehicles in 2025 will still be powered by Gasoline engines (conventional or hybrid powertrain), (the diesel market share in the light-duty segment is approximately 1% [24]). The higher penetration of HEVs, PHEVs, and BEVs makes the projected 2025 CAFE of 54.5 mpg mandated in 2012 easier to achieve without significant improvement in gasoline engine efficiency. With the addition of the right technologies, there is an opportunity to significantly improve gasoline engine efficiency at a modest increase in cost thus lowering the light-duty CO2 segment still further. Hence revisiting the CAFE fuel economy targets in light of the falling cost and higher penetration of BEVs and electrified powertrains might help explore other synergistic behaviors and further promote the advancement of electrified technologies.

Strategy for improving the efficiency of production NA and turbocharged Gasoline SI engines have converged to the following technology recipe

- Higher compression ratio with over-expanded cycles (NA - Atkinson, and turbocharged - Miller)
- Lower Bore to Stroke (BSR) ratio
- Higher amounts cooled EGR
- Faster combustion - engine design that promotes high in-cylinder turbulence along with higher energy spark plugs

Compared to a naturally aspirated engine, turbocharging reduces throttling and increases the efficiency at low and mid load and speed points where the engine spends more of the time, increasing vehicle fuel economy. The Level of downsizing (Peak BMEP) and the maximum brake thermal efficiency (BTE) of the turbocharged engine is limited by the compression ratio due to knock at low speed - high load regions. The peak BMEP of an increasing number of turbocharged engines has increased from 14-15 bar BMEP to 20-25 bar BMEP over the past decade. This has been achieved by increased combustion and knock-resistance achieved by a combination of high in-cylinder turbulence and higher energy spark plugs (to achieve fast burn rates so that the end charge is consumed before it auto ignites), improved turbocharger design, and thermal management of the engine (combustion chamber wall temperatures, etc.).

Hybrid powertrains offer significant fuel economy gains (30-40%) when compared to the base IC engine-equipped vehicle. As the degree of hybridization increases, it enables the operation of the engine in a narrow speed load range, closer to the peak efficiency island of the engine BSFC map. The engine optimized for this narrow speed load achieves higher efficiency.

The 48-Volt mild-hybrid system has the potential to significantly increase fuel economy without the safety systems and added costs of a high voltage full hybrid powertrain. The power output of such systems has increased from 10-12kW of the first generation P0 Belt integrated Starter Generators (BISG) to greater than 30kW P2 and P4 systems. The higher power output provides higher brake energy regen, electric-assist, and limited pure electric drive. 48-volt mild-hybrid system is an enabler for other efficiency improving technologies such as electrically powered accessories, electrified boosting systems, heated catalyst and aggressive cylinder deactivation, and engine start-stop.

In the long run (2030+), IC engine powertrains will have some degree of electrification to achieve the fuel economy targets. Future high-energy ignition systems in such engines will enable lean operation at $\lambda > 2$. At such dilution levels, the engine out NOx is below the threshold that needs any aftertreatment. These engines have already demonstrated brake thermal efficiency exceeding 45%. As a part of a hybrid powertrain, such lean-burn engines optimized for a narrow speed load range has the potential to achieve BTE greater than 50%.

2.0 Physics of Improving the Efficiency of a Gasoline Engine and Reducing Criteria Pollutants

Some of the technologies that positively impact one area of the engine operation have positive/ negative effects on other areas. Understanding such relationships are important for selecting technology combinations that give the highest efficiency improvements for minimal added cost and complexity. For example, implementing a Miller cycle using Early Inlet Valve Closing (EIVC) in a turbocharged engine will decrease in-cylinder turbulence, thereby reducing burn rates and increasing knock. Hence it needs to be paired with a cylinder head and piston design that increases in-cylinder turbulence and a high-energy ignition system that will maintain burn rates at lower levels of in-cylinder turbulence. This pairing is needed to realize the full potential of the Miller cycle implementation. Without such an approach, one will conclude erroneously that the Miller Cycle implementation with EIVC does not increase the brake thermal efficiency (BTE) of a turbocharged engine.

2.1 Increasing Dilution of Trapped Mass

Dilution of the stoichiometric air-fuel mixture with air or cooled Exhaust Gas Recirculation (cEGR) increases the value of the ratio of specific heats ($\gamma = C_p/C_v$) thereby increasing the work transferred to the piston during the expansion stroke [1].

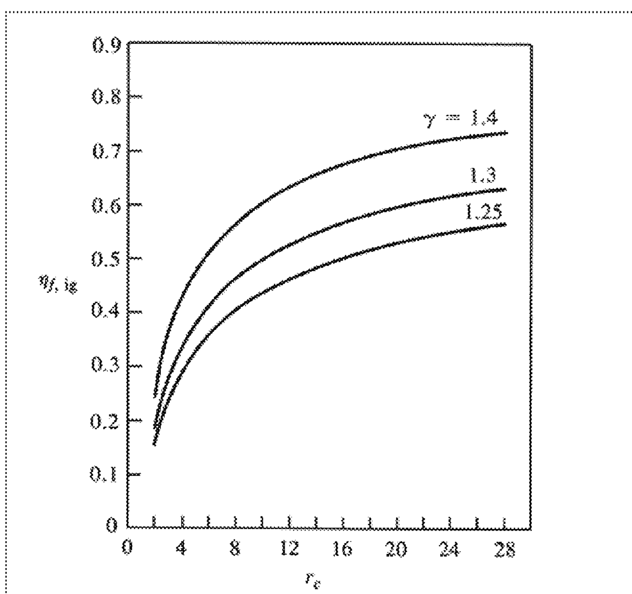


Figure 2: Ideal gas constant-volume cycle fuel conversion efficiency as a function of CR and $\gamma = C_p/C_v$ [19]

Figure 2 [19] shows the effect of Compression Ratio (CR) and γ on the fuel conversion efficiency of a constant volume cycle. The value of γ for air is about 1.4 while that of products of combustion (carbon dioxide and water vapor) is lower, closer to 1.3. The value of γ for in-cylinder mixture diluted with air is greater than that of a mixture diluted by Cooled EGR (cEGR). This gives a lean burn engine (air diluted) higher efficiency for the same equivalent dilution (ratio of fuel to the non-fuel gaseous mixture in the cylinder).

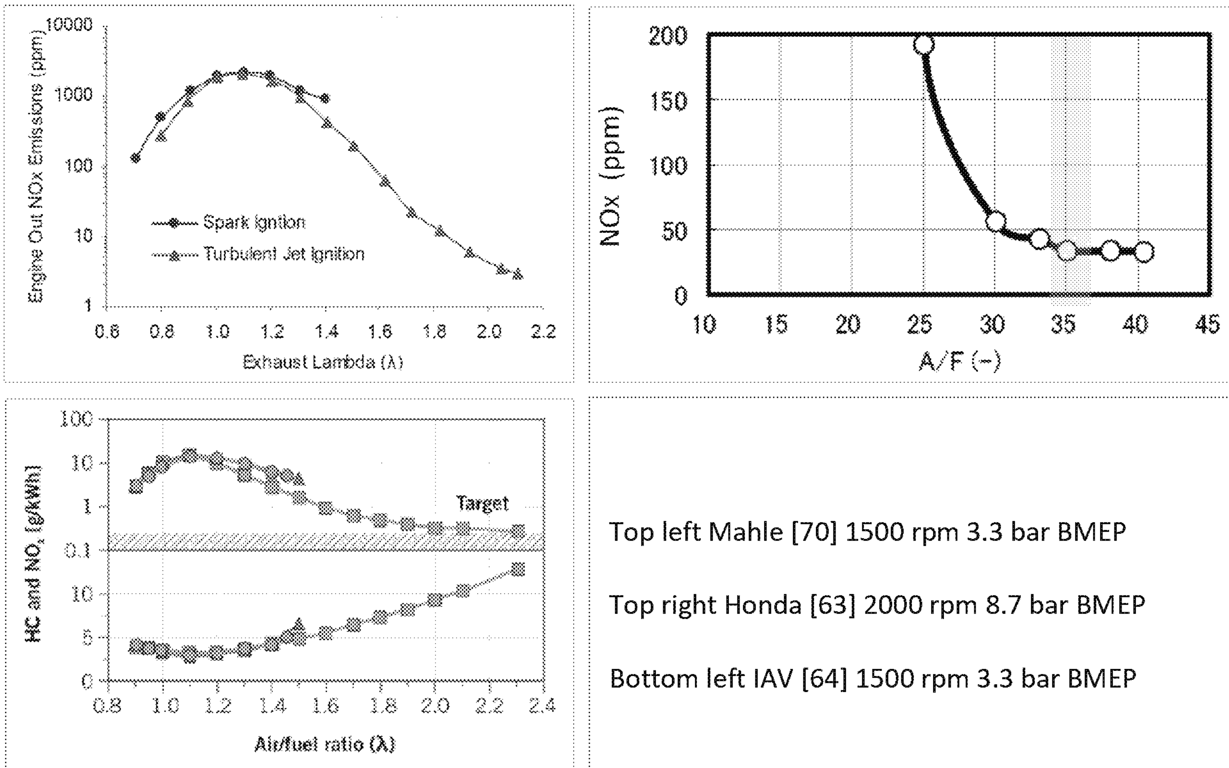


Figure 3: Low Engine NOx possible with extremely lean homogeneous mixtures

Air dilution increases the engine-out NOx and necessitates more complex and expensive aftertreatment technologies (similar to a diesel engine) like lean NOx traps, gasoline SCR systems, etc. Figure 3 shows the extremely high engine-out NOx produced with air with lean air-fuel ratios (λ between 1 and 1.6). Figure 4 shows the engine operating regions of the EU PaREGEn Engine project led by Ricardo [72]. The engine requires a diesel-like aftertreatment system shown in Figure 4 (bottom). The cost and complexity of the aftertreatment system will make this type of engine unattractive for North American applications.

Lean burn combustion with lambda > 2 reduces combustion temperatures below the NOx formation threshold lowering engine-out NOx emissions to less than 10ppm in some studies [70]. However, to operate such an engine in a wide speed load range is a challenge and will require high-energy ignition systems like an active prechamber ignition system. Figure 3 shows the engine test results from Mahle, Honda, and IAV, achieving extremely low engine-out NOx levels with the combustion of a lean homogeneous mixture (λ>2) employing an active pre-chamber ignition system (Section 11.4). Such lean-burn engines are also possible with high energy spark ignition (Nissan e-power hybrid – single-speed load point of operation) or some form of compression ignition (Mazda Skyactiv-X) by optimizing the engine to operate in a very narrow speed-load range. Figure 5 shows the different operating regions of the Mazda Skyactiv-X engine map. The engine operates in a lean air diluted Spark Plug Controlled Compression Ignition (SPCCI) mode with λ>2 in a very small portion of the engine map. This keeps the engine-out NOx low. The engine switches to cEGR diluted SPCCI for moderate loads and SI engine operation at high loads.

Such lean-burn solutions (λ>2) might still need an SCR catalyst to meet the US 2025 fleet average NMOG+NOx emissions of 30 mg/mi (Bin 30). The added cost and complexity of a NOX aftertreatment system will make lean-burn strategies less attractive.

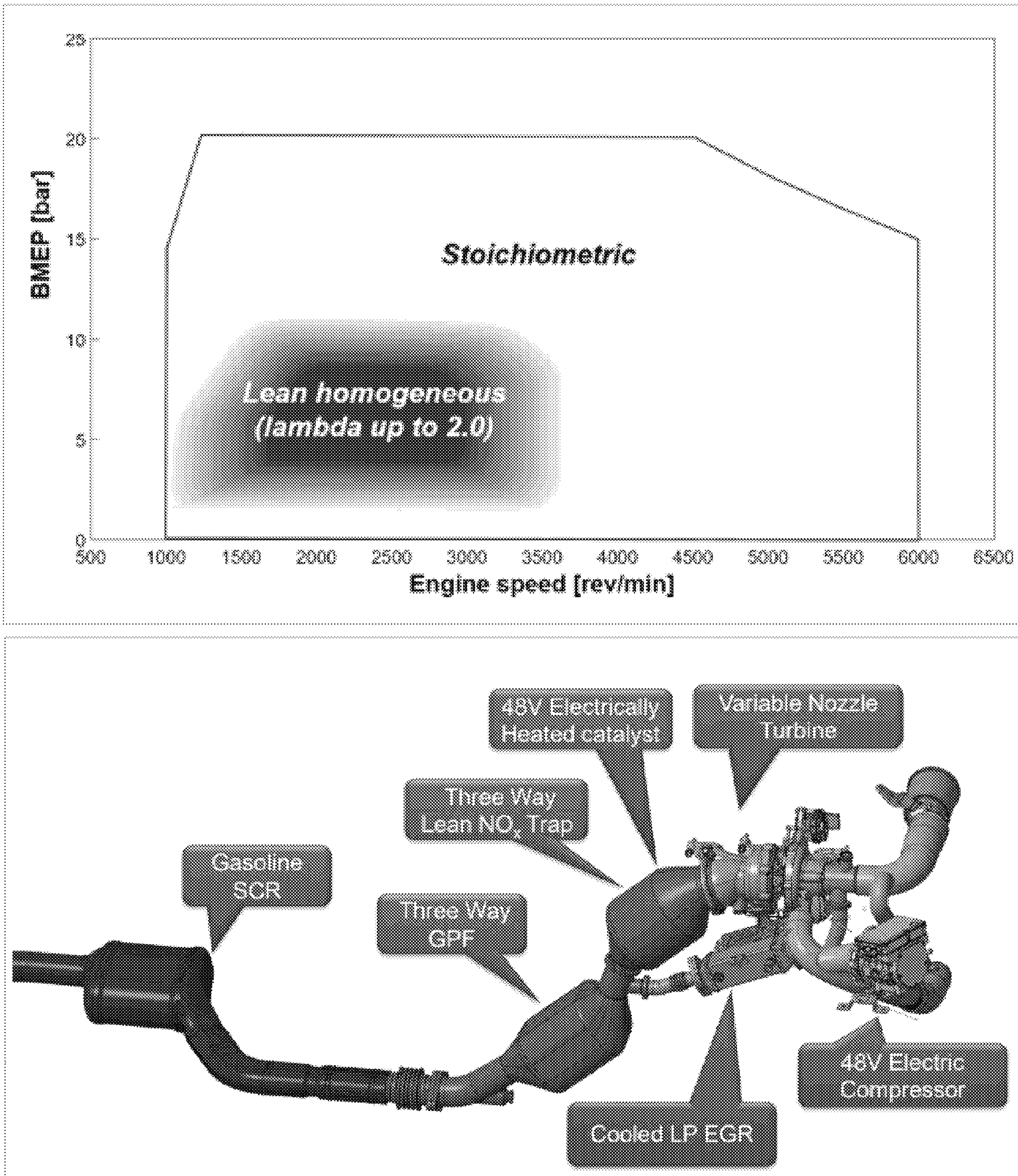


Figure 4: Operating modes and aftertreatment for a lean-burn engine – PaREGEn project [72]

Lean burn combustion with lambda > 2 reduces combustion temperatures below the NOx formation threshold lowering engine-out NOx emissions to a level that does not require any NOx aftertreatment. However, to operate such an engine in a wide speed load range is a challenge and will require high-energy ignition systems like an active prechamber ignition system. Figure 3 shows the engine test results from Mahle, Honda, and IAV, achieving extremely low engine-out NOx levels with the combustion of a lean homogeneous mixture ($\lambda>2$) employing an active pre-chamber ignition system (Section 11.4). Such lean-burn engines are also possible with high energy spark ignition (Nissan e-power hybrid – single-speed load point of operation) or some form of compression ignition (Mazda Skyactiv-X) by optimizing the engine to operate in a very narrow speed-load range. Figure 5 shows the different operating regions of the Mazda Skyactiv-X engine map. The engine operates in a lean air diluted Spark Plug Controlled Compression Ignition (SPCCI) mode with $\lambda>2$ in a very small portion of the engine map. This keeps the engine-out NOx low and negates the need for any NOx aftertreatment. The engine switches to cEGR (G/F lean in re 4) diluted SPCCI for moderate loads and SI engine operation at high loads.

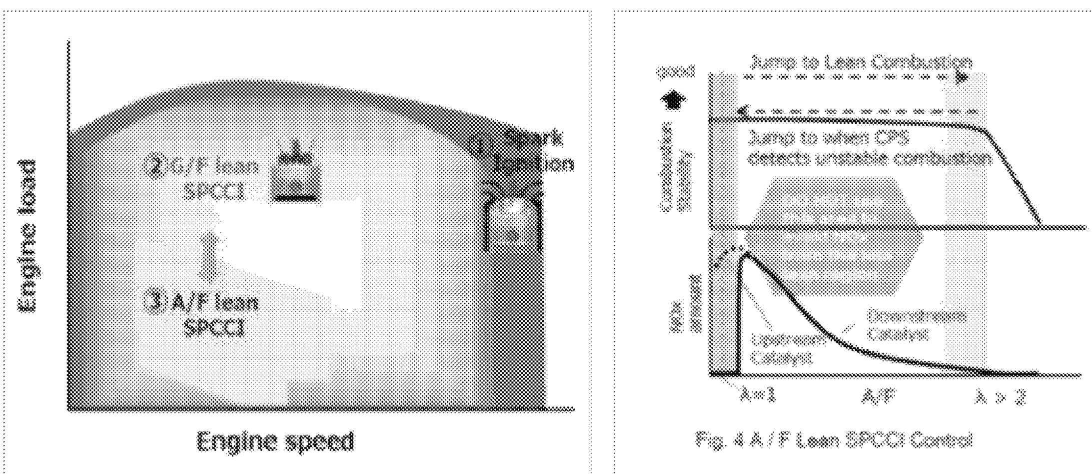


Figure 5: Mazda Skyactiv-X engine – engine map operating regions

A Three-Way-Catalyst (TWC) can be used for the aftertreatment of a cEGR diluted engine that operates on a stoichiometric air-fuel ratio making it simple and cost-effective. Several Naturally Aspirated (NA) and turbocharged engines currently in production use increasing amounts of cEGR. cEGR also improves engine efficiency and emissions by

- Reducing the amount of intake throttling at low and mid loads lowering the pumping work.
- Lowering peak combustion temperatures, reducing the heat transfer losses.
- Lowering combustion temperatures resulting in lower NOx emissions

The low burn rate of cEGR diluted engines necessitates an early start of combustion (spark timing). This results in part of the heat release and pressure rise taking place during the compression stroke resulting in negative work and reduced efficiency. cEGR dilution decreases the reactivity of the in-cylinder mixture and delays the autoignition of the end charge. If the same burn rates are maintained, cEGR dilution will increase the knock resistance of an engine. But this decreased reactivity also reduces the flame speeds and burn rates. This results in very little knock resistance due to cEGR being realized[28, 29].

The following technologies can enable increased dilution of the air-fuel mixture in future engines

- high in-cylinder turbulence – Design of the intake port, piston top, valve angle, valves, etc. to increase in-cylinder turbulence
- High energy volume ignition systems – These systems produce multiple ignition sites in extremely dilute mixtures resulting in high burn rates and low cycle to cycle variation under such conditions.
- Alternative combustion regimes that burn the in-cylinder charge using compression ignition - Homogeneous Charge Compression Ignition – HCCI, Spark Assisted Compression Ignition – SACI (Mazda Skyactiv-X)
- Increase reactivity of the in-cylinder mixture – producing Hydrogen (H2) rich gas from the fuel to increase the reactivity of dilute mixtures (Section 10.0)

2.2 Reducing Pumping Work

Throttling the intake (reducing intake pressure) for load control increases the negative work during the intake process (increases the area of the pumping loop in the Pressure-Volume (PV) diagram) reducing the efficiency of an engine. Technologies that reduce throttling reduce pumping and increase the efficiency of an engine.

- Variable valvetrain – variable lift, duration, and phasing mechanisms. cam switching
- Downsizing – forced induction
- Cylinder deactivation – fixed and advanced (example: Tula Dynamic Skipfire) cylinder deactivation
- Charge dilution - Lean burn (air diluted) or Cooled EGR
- Internal EGR – Internal EGR at non-knock limited operating points increase in-cylinder charge temperature, reducing its density and amount of throttling required. Higher temperature also increases the mixture reactivity increasing the cooled EGR tolerance at low loads. The Toyota A25A-FKS (2.5 -liter 4-cylinder used in the Toyota Camry and Rav4) traps an increased amount of internal residuals by using Negative Valve Overlap (NVO) [12].

2.3 Overexpanded Cycle – Atkinson/ Miller cycle

An engine with a high geometric compression ratio with an effective volumetric compression ratio lower than the effective volumetric expansion ratio is an effective method for increasing engine efficiency. In production engines, the overexpanded cycle is implemented by either Early Intake Valve Closing (EIVC) or Late Intake Valve Closing. Examples of such engines include the 2.0-liter Mazda Skyactiv-G (EPA HCR1 engine), Toyota (A25A-FKS, 2GR-FKS), Audi EA888 2.0L, VW EA211 EVO 1.5L, etc. The shorter intake stroke results in an engine taking in less charge per cycle requiring a larger displacement engine to maintain the same torque/power level as a non-Atkinson/ Miller engine. For turbocharged engines, the loss in intake stroke volume can also be compensated by increased boost pressure. Turbocharged miller cycle engines have lower exhaust temperatures (due to a higher expansion ratio) reducing the need for enrichment at high loads (for component protection) when compared to a non-Miller turbo engine.

One of the challenges of using EIVC and LIVC strategies is the reduction in turbulence at the end of the compression stroke [30, 31, 32]. Figure 6 [31] shows how the in-cylinder Turbulent Kinetic Energy (TKE) changes with EIVC and LIVC strategies when compared to the baseline engine. This reduction in TKE results in low burn rates and combustion instability. In some cases, this can even lead to reduced efficiency and emissions when compared to the baseline engine.

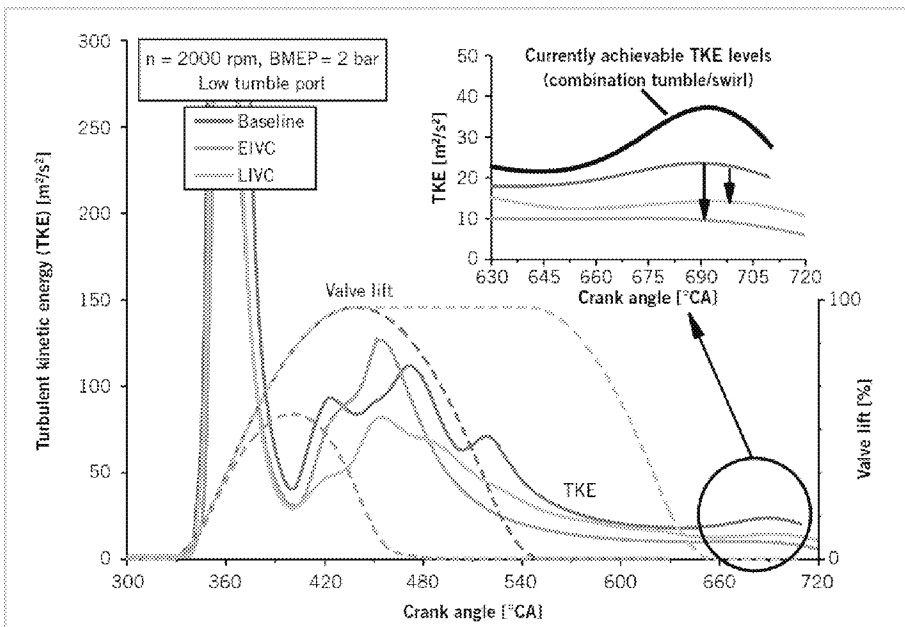


Figure 6: Turbulent Kinetic Energy (TKE) in EIVC/ LIVC compared to baseline lift [31]

Figure 7 shows the design optimization that was required for the Audi EA888 Gen3b (2.0-liter, 4-cylinder) engine (which implements the Miller cycle by EIVC) to maintain the in-cylinder turbulence levels of the previous generation non-Miller cycle engine. Though adding Miller cycle to a base turbocharged engine does not require any additional hardware, it entails engine design optimization to maintain in-cylinder turbulence and burn rates.

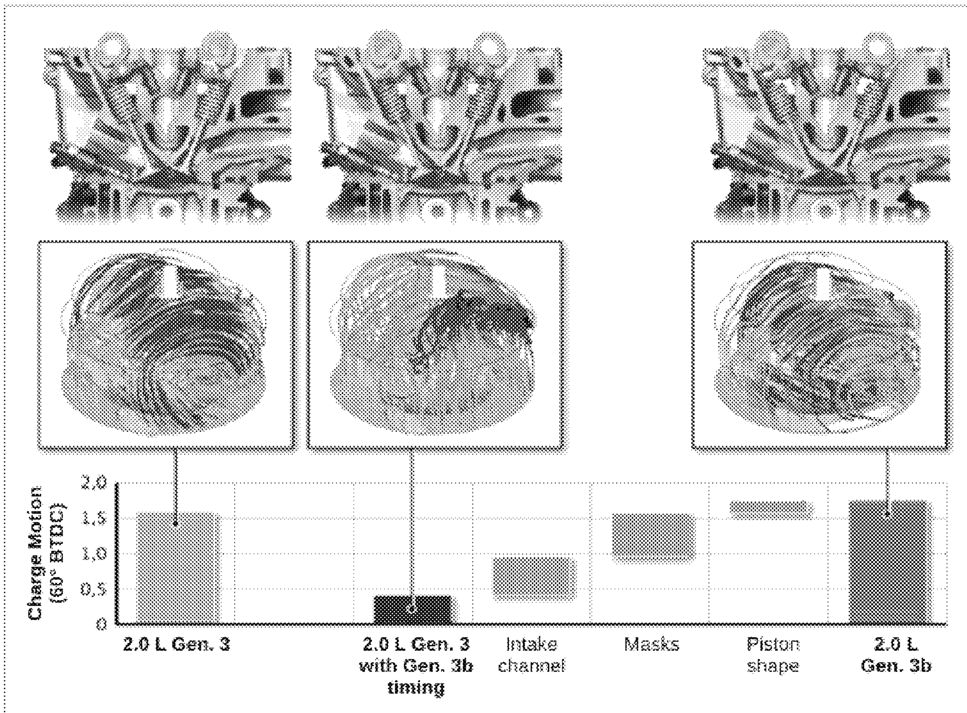


Figure 7: Design optimizations to maintain charge motion, Miller cycle with EIVC in an Audi EA888 Gen3b Engine [40]

The following technologies can enable future Atkinson/ Miller cycle engine with higher geometric compression ratios and higher Miller/ Atkinson ratios

- High energy volume ignition systems (see section 11.0) that reduce the reliance on in-cylinder turbulence for achieving high burn rates
- Lower bore-to-stroke ratio (BSR)
- Engine design elements that increase in-cylinder turbulence (TKE) at part load without negatively affecting volumetric efficiency at high loads– optimized cylinder head, port, and piston crown geometry, optimized intake valve lift/ variable valve lift to increase intake charge velocity, tumble flaps in the intake port, etc.

2.4 Low Bore to Stroke Ratio (BSR)

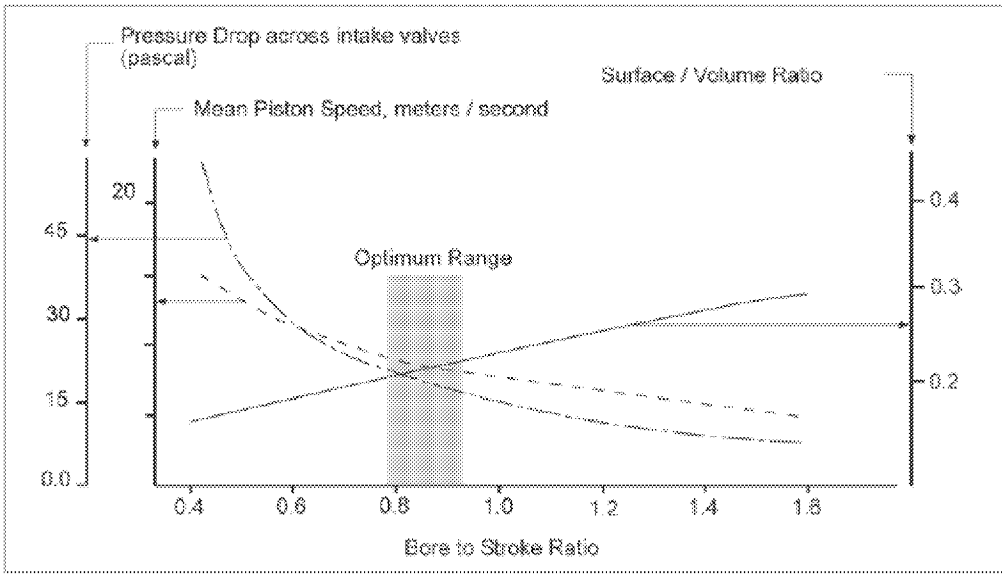


Figure 8: Effects of variables determining optimum bore to stroke ratio [74]

Figure 8 [74] illustrates the variation of the three major factors that determine the optimum bore-to-stroke ratio of an engine: the piston speed, surface-to-volume ratio, and pressure drop across the intake valves. The optimum bore to stroke ratio is determined by the following considerations [74].

- **Mean piston speed:** longer stroke increases the average piston speed and limits the maximum rpm of the engine. Table 2 gives the average piston speeds of some production engines. As can be seen, most engines today, turbocharged or NA, do not go up to the limit of average piston speed (about 25 m/s) enabled by today's technology. The fraction of time that light-duty engines spend at high (near maximum) engine rpm over test cycles or real-world driving is very small for it to be a durability concern. A Ford 2.7 Ecoboost engine has an average piston speed of 13.8 m/s. If the bore and stroke were changed to 73 and 109 resulting in a BSR of 0.67 (displacement not changed), the mean piston speed will only be 18.1 m/s at 5000 rpm).

Table 2: Piston speed of production engines

OEM	Engine	Configuration	Disp	CR	Mx Power	Engine speed	Hp/liter	Max torque	Bore	Stroke	Bore to Stroke Ratio	Mean piston speed
			cc		bhp	rpm		Nm	mm	mm		m/s
Honda	B18C	I4 NA	1797	10.6	197	8000	109.6	134	81	87.2	0.93	23.3
Audi	R8 V10	V10, NA	5204	12.7	540	8250	103.8	560	84.5	92.8	0.91	25.5
Honda	K20C1	I4 TC	1996	9.8	306	6500	153.3	400	86	85.9	1.00	18.6
GM	LS3	V8 NA	6162	11.5	455	6000	73.8	617	103.25	92	1.12	18.4
Toyota	A25A-FKS	I4 NA, Atkinson	2487	13	203	5000	81.6	249	87.5	103.4	0.85	17.2
Honda	L15B7	I4 TC	1497	10.6	174	6000	116.2	220	73	89.4	0.82	17.9
Mazda	Skyactiv PY-VPS	I4 NA, Atkinson	2488	13	187	6000	75.2	252	89	100	0.89	20.0
Ford	2.7 Ecoboost	V6 Turbo	2694	10.3	335	5000	124.4	542	83.06	83.06	1.00	13.8

- **Pressure drop across the intake valves**: larger bore-to-stroke ratios enable increased valve sizes resulting in high curtain area (area of flow) resulting in low pressure drop across the valves and high volumetric efficiency. The volumetric efficiency of a low bore to stroke ratio engine decreases at high RPM resulting in torque and power that falls off earlier in the engine speed range. Manufacturers share engines across product lines to keep unit costs low and the "low RPM nature" of a low bore to stroke engine may be suitable for one vehicle but not for another. For example, the 2.7-liter 4-cylinder L3B engine is shared by the Chevy Silverado, a pickup truck, and the Cadillac CT4-V, a high-performance sedan. Having a very low bore-to-stroke ratio would make the engine unsuitable for a performance sedan. The same is true for the small-block engine architecture from GM that is shared by pickup trucks, SUVs, and the corvette.
- **Heat transfer:** Lower BSR reduces the surface area-to-volume ratio of the combustion chamber (especially near combustion TDC), reducing combustion heat transfer. As the compression ratio is increased, the surface-to-volume ratio of the combustion chamber increases increasing heat transfer losses negating some of the efficiency gains. This effect is particularly important in Atkinson and Miller cycle engines that have a very high geometric compression ratio. Figure 9. shows the effect of BSR and compression ratio on the fuel consumption (efficiency) improvement of an engine [39]. At a BSR of 1, increasing the compression ratio above 13 gives negligible fuel economy benefit.

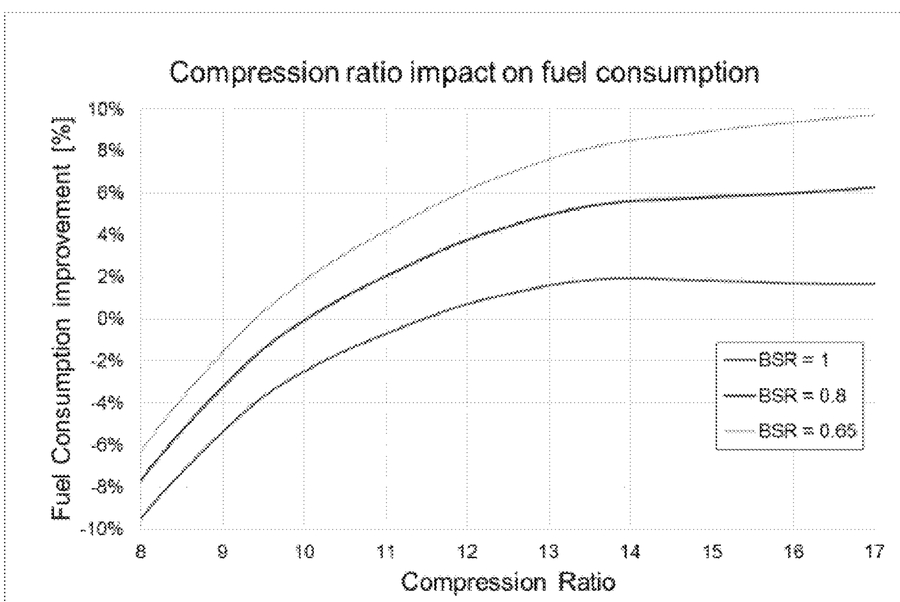


Figure 9: Effect of Compression Ratio and Bore to Stroke Ratio (BSR) on fuel consumption improvement [39]

- **Knock resistance due to flame travel distance:** A smaller bore-to-stroke ratio reduces the flame travel distance reducing heat release duration (increase the fraction of constant volume combustion). The reduced combustion duration also decreases knock (less time for the end gas to get to auto-ignition conditions). This enables a higher compression ratio.

- **In-cylinder turbulence and burn rates**: The in-cylinder turbulence increases with piston speeds. Low bore to stroke ratio results in higher piston speeds at the same RPM and engine displacement. The higher turbulence results in faster burn rates and a lower propensity for knock. (Less time for the end gas to get to auto-ignition conditions). This enables a higher compression ratio.
- **Engine dimensions:** longer stroke increases the engine height and introducing packaging challenges since manufacturers share engines across vehicles. A tall engine will be easy to fit in an SUV but difficult in a sedan with a low hood. There are solutions like installing the engine at an angle this, but this increases complexity and the inability to share powertrain components across vehicles.

Honda, Toyota, Ricardo, SWRI, ORNL [72, 73, 75-79] have all concluded that a low BSR of up to 0.67 (stroke to bore ratio of 1.5) is an enabler for the next generation gasoline engines (turbo, dilute- air/ cEGR, miller) with BTE exceeding 45%. Having a low bore-to-stroke ratio engine as a part of a hybrid powertrain, the electric motor torque can be used to overcome the high RPM wide-open throttle performance penalty of a low BSR engine [79].

2.5 Reducing Heat Transfer Losses

A typical SI engine rejects roughly a third of the heat produced during combustion to cylinder walls and a third to the engine coolant. Enabling technologies for reducing the heat transfer losses include:

- Increased trapped charged dilution decreases combustion temperatures reducing heat transfer losses
- Low BSR engine design decreases the surface-to-volume ratio of the combustion chamber reducing the heat transfer losses.
- Split cooling – Separate cooling circuits for the block and head can maintain the head and the block at their optimum temperatures. Colder cylinder heads to prevent knocking and enable high compression ratios. Hotter cylinder walls to reduce heat transfer losses and decrease friction. Split cooling also enables faster warmup of the combustion chamber increasing combustion stability and reducing emissions during cold starts
- Thermal Barrier coatings

2.6 Summary

Figure 10 shows how different technologies affect various aspects of engine operation. Positive effects are shown in green and negative effects in red. For example, cooled EGR increases the ratio of specific heat of the in-cylinder charge and decreases heat transfer losses increasing engine efficiency. But at the same time, it negatively affects combustion stability and burn rate. Hence it will be beneficial to pair it with a high-energy ignition system and a low bore-to-stroke ratio engine design. There are some weak interactions like how compression ratio (for the same bore to stroke ratio) affects heat transfer etc., which have not been ignored in Figure 10.

	Pumping work	The ratio of specific heats of the trapped mass	Combustion stability, burn rate	Knock	Heat rejection	NOx	NVH
High Compression ratio				●			
Miller/ Atkinson cycle			●	●			
Air diluted - lean burn (1<λ<2)	◍	◍	●		◍	●	
Lean burn, air diluted - (λ>2)	◍	◍	●		◍	◍	
cEGR Diluted	◍	◍	●		◍	◍	
Internal EGR	◍		◍	●			
Downsizing	◍			●		◍	
High energy volume ignition systems			◍	◍	◍		
Engine Geometry - low bore to stroke ratio			◍	◍	◍		
SACCI (cEGR Diluted, Lean λ>2)	◍	◍			◍	◍	●

Figure 10: How technologies affect different aspects of engine operation

3.0 Transmission technologies

Figure 11 from the EPA Trends Report [25] shows that in 2020, 80% of light-duty vehicles sold in the US market (in 2020) were equipped with a Continuously Variable Transmission (CVT) or an automatic transmission with seven or more ratios. In 2021-22 more vehicles are expected to move to a transmission with eight or more ratios. More than eight transmission ratios give negligible fuel economy benefits and features like lockup torque converters and other technologies to reduce friction, weight and hydraulic losses have high penetration. Hence, we consider transmission as a mature technology with very little unrealized efficiency/ fuel economy benefits.

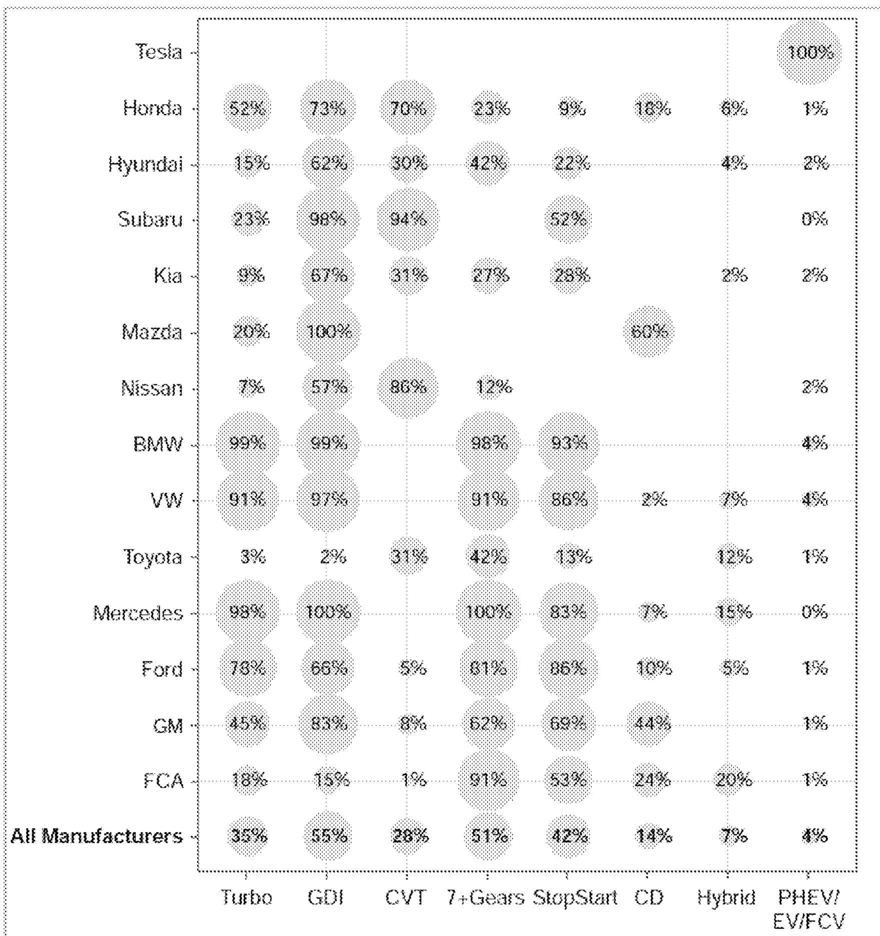


Figure 11: Technology Share for Large Manufacturers, model-year 2020 [25]

4.0 Naturally Aspirated Engine Pathway

Figure 11 from the EPA Trends Report [25] shows that in 2020 about 35% of vehicles were turbocharged (2019 - 34%, 2018 - 21%), leaving a large portion of the new US light-duty fleet powered by NA engines. NA engines are found in small economy class vehicles to full-size pickups with class-leading towing capacities. One type of NA engine has overhead cams and Variable Cam Timing (VCT) on intake and exhaust valves and available in 4-cylinder (about 2.5 liters), V6 (about 3.5-3.6 liter), and V8 (5-5.7 liter) configurations. The second type of NA engine is large single-cam pushrod V8 engines in the 5.5 to 6.7-liter displacement.

Table 3 shows some of the engines in the first category and the technologies they employ. Different manufacturers follow different orders in which efficiency-improving technologies are added to their engines. This differs from a rigid order of technology adoption used by NHTSA for CAFE modeling.

Table 3: Example of Small NA engines used in small and midsize vehicles

Engine	Technology	NHTSA Engine Technology
Toyota A25A-FKS 2.5L, 4cyl, I4 (Camry, Rav4)	CR 13, DI+ PFI, Dual VVT (int electric, ex- hydraulic) Atkinson cycle, Cooled EGR (up to 25%) Variable capacity oil pump High energy ignition system (Tier 3 fuel)	HCR1+ cooled EGR
Mazda Skyactiv-G 2.5L, 4cyl, I4 (CX5, Mazda6)	CR 13 + DI + Dual VVT Atkinson Cycle, Cylinder Deac (tier 3 fuel)	HCR1+ Cylinder deac
Toyota 2GR-FKS 3.6L, V6 (Tacoma)	CR 13, DI+ PFI, Dual VVT Atkinson cycle, Cooled EGR (tier 3 fuel)	HCR1+ cooled EGR
FCA 3.6L Pentastar Ram 1500	CR 11.3, PFI, Dual VVT with switching intake cam lobes, Cooled EGR	Engine 1 + VVL + Cooled EGR

Figure 12, shows the probable technology pathway for NA engines with dual overhead cams. Mazda added fixed cylinder deactivation to their "HCR1" technology level engine while Toyota added cooled EGR. Implementation of cylinder deactivation is very dependent on the loading of the engine on test cycles and real-world use. For example, a vehicle with a large lightly loaded engine will yield higher fuel economy benefits by adding cylinder deactivation since more of the test cycle and real-world driving conditions can be handled by the engine in the cylinder deactivated mode (example: full-size SUV with a NA V8). It also depends on the transmission and the drivelines' ability to smooth out torsional vibrations and the NVH targets for the vehicle (and expectations for the segment it completes in. Premium and luxury vehicles have a lower tolerance of NVH). With a small, more heavily loaded engine, only a small portion of the use case can be covered by the cylinder deactivated mode, hence the benefit of the technology in such cases is limited.

Both cooled EGR and cylinder deactivation decrease pumping. Having deployed one of these technologies, the additional benefit of implementing the other might be very small depending on the vehicle application and how well the first technology has been implemented. In short, combining the two technologies, cooled EGR and cylinder deactivation (HCR2 engine) might not apply to a 4-cylinder engine used in a midsize vehicle. However, there is a case for an advanced deactivation system (like the Tula Skip fire) combined with a 48V P2 hybrid. The electric motor can actively smooth out the torque pulses due to more aggressive deactivation strategies. Also, the electric motor can provide transient torque during driver tip-in enabling the engine to remain in cylinder deactivated mode for more of the time. A new generation of high power 48V systems (up to 30kW) can provide capabilities rivaling that of a full hybrid in a small or midsize vehicle without the cost associated with a high voltage hybrid [41,42]

Further efficiency improvement for the NA engine is contingent on high cEGR dilution without negatively affecting burn rates. This would require low Bore to Stroke Ratio (BSR) engines with high in-cylinder turbulence and/or some form of in-cylinder fuel reforming and high-energy spark plugs (or multiple spark plugs). The amount of the EGR dilution can be increased further while maintaining high burn rates and low COV of IMEP by using high-energy-volume ignition systems. Technologies in increasing order of charge dilution they enable are Plasma ignition systems < Passive prechamber < active prechamber. Active prechamber and microwave ignition systems can enable air diluted engine operation at $\lambda>2$. The low combustion temperatures at such high air dilution can result in engine-out NOx concentrations less than 10ppm. lean-burn engines even at such high dilution rates might require an SCR system to meet the 2025 Fleet average NMOG+NOx limit of 30 mg/ mile (Tier 3 Bin 30). Though lean-burn engines have higher BTE when compared to the cEGR diluted engines, (Figure 2), If they require an SCR system to meet NOx standards, the added complexity and cost will make them unattractive for volume production.

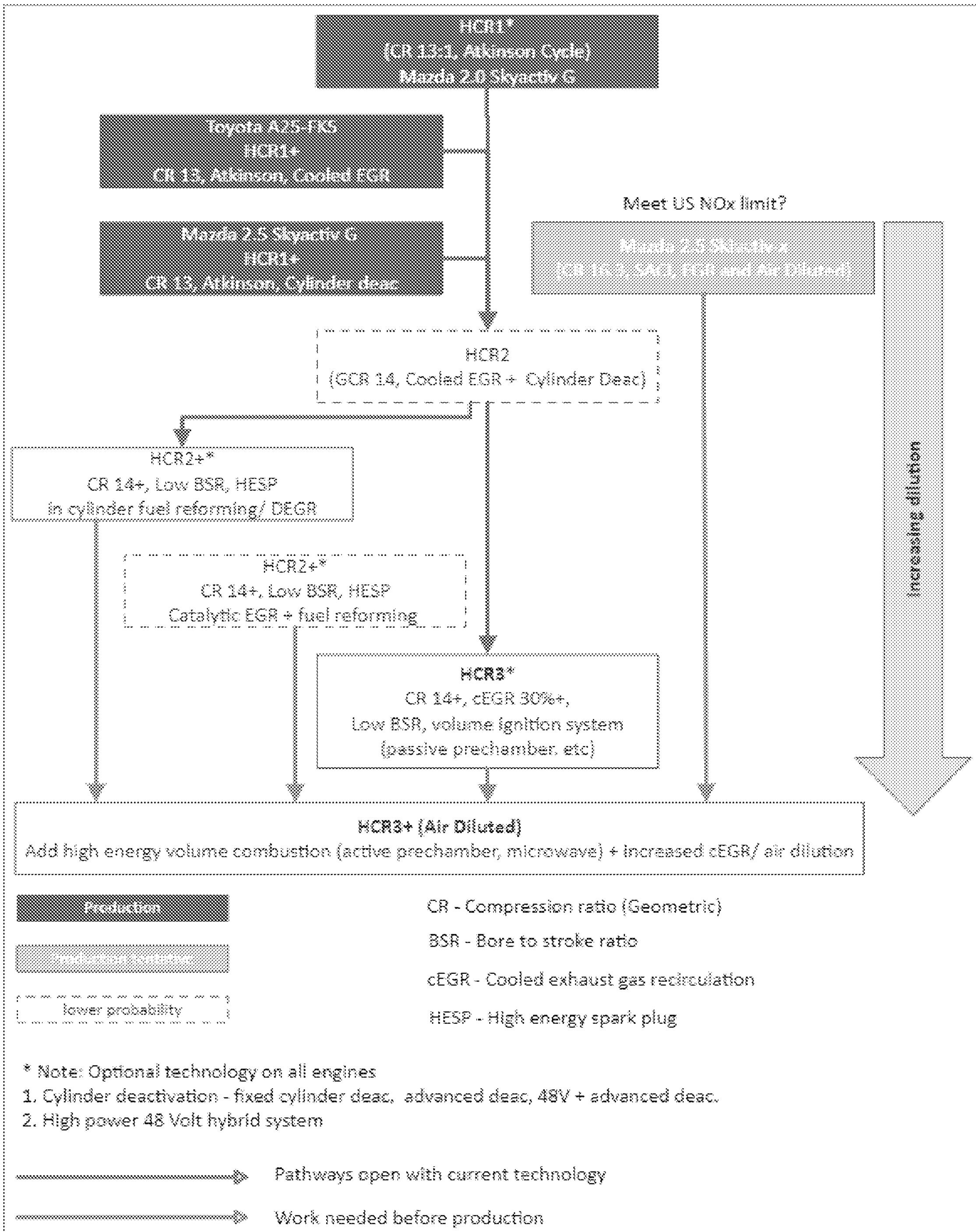


Figure 12: Naturally Aspirated (NA) engine pathway

Figure 13 gives a probable future technology pathway for large single-cam pushrod V8 engines. The state-of-the-art engine of this type in production today has a CR of 11.5:1, direct injection, and single cam phasing, and advanced cylinder deactivation (Tula Dynamic Skip Fire). The single camshaft phasing results in a fixed overlap between the intake and the exhaust valve timing. Technology for independent intake and exhaust valve phasing on a pushrod is available from suppliers like the DouCam™ system from Mechandyne (in production in the 2013-2017 Dodge Viper).

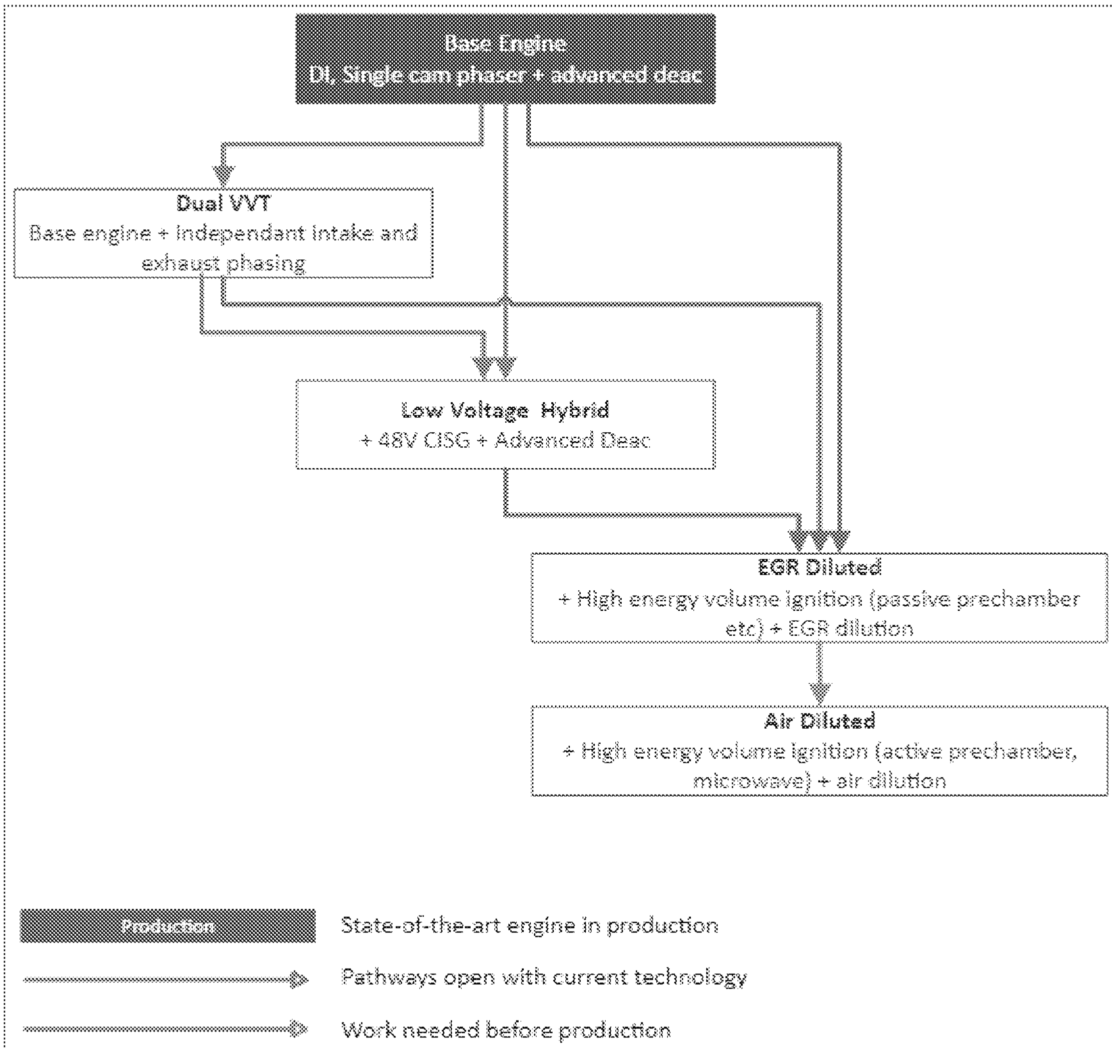


Figure 13: Technology pathway for large bore cam in block engines

These engines go in full-size SUVs and pickups that have a high tow rating but operate under very light loads most of the time. Technologies like fixed and advanced deac systems are very well suited for such applications. GM uses Tula Technologies' Dynamic Skip Fire (DSF) system (NHTSA technology classification - advanced deac) on their V8 engines. The efficiency gain from an advanced deac system is limited by NVH concerns due to the torque pulsation resulting from the lower number of firing cylinders. Combining a 48V P2 mild hybrid system with advanced deac can actively smooth the torque pulses and enable more aggressive deac strategies with a lesser number of firing cylinders. Also, the electric motor can provide transient torque during driver tip-in enabling the engine to remain in deac mode for more of the time. With the latest generation of 48-Volt systems from major suppliers with a power output of up to 30kW, they can provide a much higher level of hybrid assist even for a large vehicle like a pickup truck. Such systems can also provide smoother start-stop and electric creep. With the added battery capacity of the 48V system, all accessories including the HVAC compressor can be run electrically reducing engine idle.

Implementing the Atkinson cycle in these engines presents challenges due to their large bore diameters (approximately 99 to 104mm) resulting in the long-distance the flame front has to travel increasing the knock propensity of the end charge. Valve strategies (EVC) used for implementing the Atkinson cycle will reduce in-cylinder turbulence (see section 2) lowering burn rates and increased knock. With an Atkinson cycle, these engines will have to be made larger to maintain their power output. The use of high EGR dilution presents similar challenges due to the increased dilution lowering burn rates. This limitation can be overcome by using a combination of engine design and an appropriate ignition source, as shown below, that can ensure fast combustion of dilute mixtures

- Optimized engine design for high in-cylinder turbulence + high energy spark plug
- Multiple spark plugs per cylinder
- Volume ignition systems like Corona Ignition (see section 8)
- Passive or active prechamber combustion systems, microwave ignition, etc. (See section 8)

The flame travel distances can be reduced by switching to a lower Bore to Stroke Ratio engine design. Unlike a Dual Over Head Cam (DOHC) engine (like the Toyota A25A-FKS) with four valves per cylinder, pushrod engines have 2 valves per cylinder limiting the curtain area available for flow. Hence the combustion and efficiency benefits of low bore to stroke ratio design will have to be weighed against the ability to maintain volumetric efficiency to meet the power output requirements. In short, the combination of bore-to-stroke ratio, engine design for increasing in-cylinder turbulence, and the appropriate ignition source will have to be optimized.

Cam-in-block engines are simple and cost-effective making them candidates as the base engine for a hybrid powertrain. For a hybrid-specific application, the BTE of the engine can be increased by optimizing it to operate in a narrow speed load range of the engine operating map.

5.0 Downsized/ Boosted Engine Pathway

Downsizing of engines has emerged as one of the most effective and widely used technologies for increasing vehicle fuel economy and improving GHG performance. In 2020 about 35% [25] of new light-duty vehicles sold in the US were powered by turbocharged engines.

The peak efficiency of a state-of-the-art naturally aspirated engine is higher than a turbocharged one with comparable technology content, the principal reason being the higher compression ratio of the NA engine. But at light loads where the engine operates most of the time, the downsized engine is less throttled (owing to its smaller size) and hence more efficient. Figure 14 compares the brake thermal efficiency of the Honda 1.5L L15B7 turbo engine (left) to the 2.5L Toyota A25FKS NA engine on the right used competing midsize SUVs and Sedans [37,38]. The peak brake thermal efficiency of the Toyota engine is 39% while that of the Honda is 37%. But at 2000 rpm 50Nm, the efficiency of the Toyota engine is 30% while that of the Honda is 32.5 %. The Honda 1.5-liter turbo engine mated to a CVT gives an EPA rating of 28/34 (city/ highway) mpg in a CRV while the Toyota 2.5-liter NA engine mated to an 8-speed transmission gives an estimated 27/35 mpg in the RAV4. Two different powertrain strategies resulting in almost identical fuel economy.

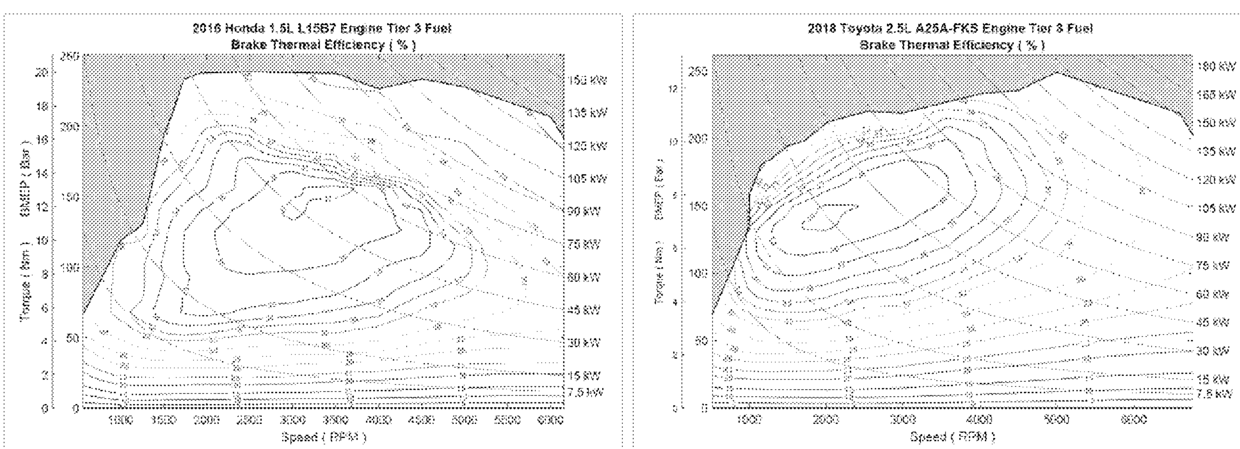


Figure 14: Comparison of State-of-the-art NA and Turbo engine efficiencies [37], [38]

Downsized engines are knock limited at high loads, necessitating retarding the spark timing and the 50% fuel mass fraction burned, well past the crank angle (6-8 degrees after top dead center) for maximum efficiency. Also, many engines need fuel enrichment at high loads for cooling the in-cylinder charge to control knock and keep exhaust gas temperatures under control for component (turbine) protection. To realize the full efficiency potential of downsizing, a turbocharged engine has to be matched to transmission and vehicle such that the engine operation at high loads is limited to a very small fraction of the drive cycle. If the engine spends more than a small fraction of the time operating at high loads, the engine has to be designed to minimize combustion retard and fuel enrichment to maintain the advantages of downsizing. Cooled EGR has limited ability (see section 2.1) to reduce knock in turbocharged engines.

Table 4 shows some of the state-of-the-art turbocharged engines in production in North America and

Europe. The table shows how different manufacturers add incremental engine technologies in different orders.

Table 4: State of the art downsized engines and the technology content

Engine	First year of production (NA)	Configuration	Displacement	Compression ratio	Bhp	Bhp/ Liter	Torque (Nm)	Peak BMEP	Bore to stroke ratio	Twin cam phasing	Variable intake valve lift	Cooled EGR	Miller Cycle	Variable geometry turbine	48V + E-supercharger / E-turbo	Discrete cylinder deactivation	Variable compression ratio	Spark Assisted Compression Ignition	Lean burn	Prechamber ignition
Honda L15B7	2016	I4	1.5	11	174	116	162	14	0.80	●										
Mazda Skyactiv-G Turbo	2016	I4	2.5	11	250	100	430	22	0.89	●		●	●	1						
VW EA211 EVO 1.5	2017	I4	1.5	13	150	100	184	15	0.87	●			●	●		●				
Nissan MR20 DDT VCR	2018	I4	2.1	8-14	268	128	390	23	0.89	●			●				●			
Mazda Skyactiv-X SPCCI	?	I4	2.0	16	178	89	224	14	0.95	●		●	●					●	●	
Mercedes M256	2017	I6	3.0	11	429	143	520	22	0.90	●	●				●					
JLR AJ300	2019	I6	3.0	11	395	132	550	23	0.90	●					●					
Maseratti Nettuno	2021	V6	2.8	11.0	621	222	730	33	0.93	●										●
Ford 2.7 ecoboost gen 2	2018	V6	2.7	10.0	325	120	542	25	1.00	●		●								
Ford 2.3 ecoboost Ranger	2019	I4	2.3	9.7	325	141	420	23	0.94	●		●								
Mercedes M139*	2022	I4	2.0	9.0	443	222	420	26	0.90	●					●					

1 - Mazda uses unique valving to implement a pulse/ constant pressure turbocharging system

* Next generation Mercedes C63 PHEV Powertrain. (pre production numbers)

Figure 15 outlines a probable technology pathway for turbocharged engines. The next step in the evolution of turbocharged engines will be advanced boosting systems like variable geometry turbochargers, 48-volt hybrid + electric supercharger + turbocharger, 48-Volt hybrid + electrically assisted turbocharger (see section 9.0 for details). These engines will have lower bore-to-stroke ratios, higher geometric compression ratio with Miller cycle, and high energy spark plugs.

A significant increase in efficiency of turbocharged engines requires reduction/ elimination of knock. This can be achieved by extremely fast combustion initiated by high-energy volume ignition systems. These systems produce multiple ignition sites throughout the combustion chamber so that all the in-cylinder charge is consumed before the end charge auto-ignites. The peak in-cylinder pressures of such an engine will be similar to that of a diesel. Technologies in increasing order of charge dilution they enable are high energy spark plugs< multiple spark plugs < Plasma ignition systems < Passive prechamber < active prechamber. Fast combustion of cEGR diluted air-fuel mixture can be enabled by some form of fuel reformation (section 10.0) that increases the reactivity of the in-cylinder mixture.

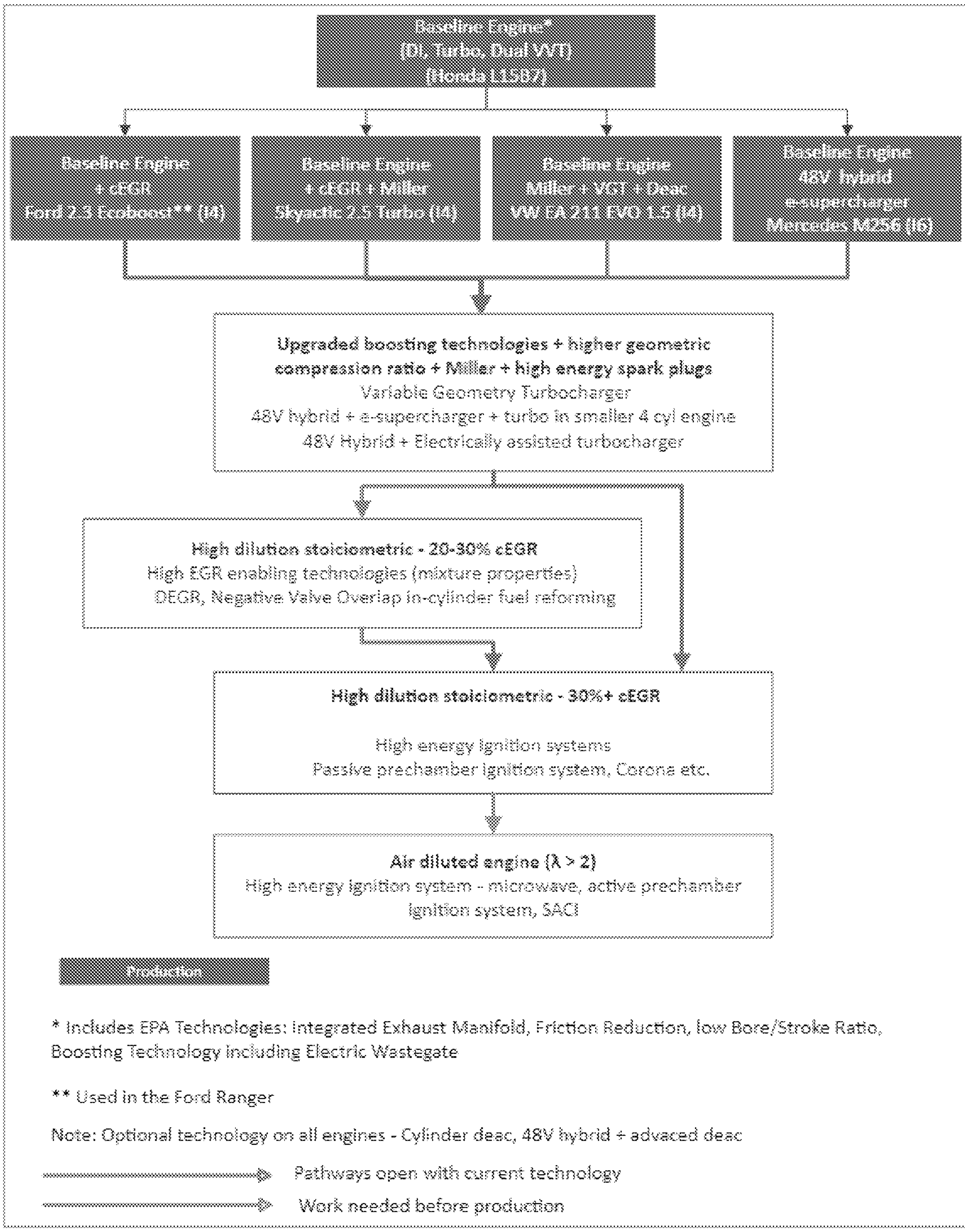


Figure 15: Turbocharged engine pathway

6.0 48 Volt Hybrid System

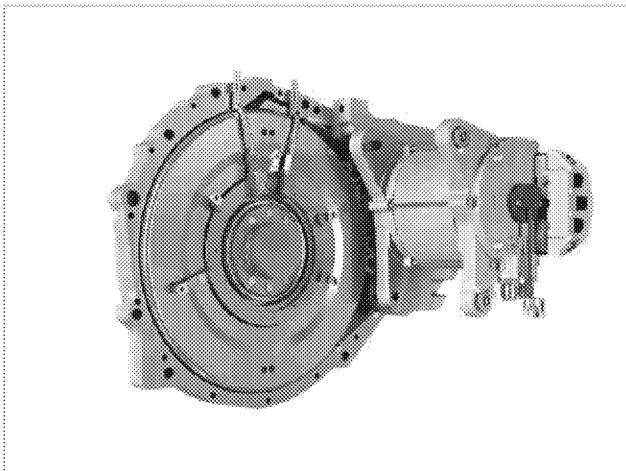
Apart from the electrical motor assist, a 48-volt system can be thought of as an enabler for many high-efficiency engines and vehicle technologies including:

- Electrically driven accessories – water pump, HVAC compressor.
- Meeting energy requirements of high energy ignition systems (section 11.0), future ADAS systems
- Electrically assisted boosting technologies – electrically assisted turbocharger, electric supercharger (Section 9.0).
- Electrically heated catalyst – quick heat-up of the catalyst during cold start, maintaining catalyst temperatures at low loads, enabling more aggressive start-stop strategies.

The first generation of 48-volt systems were P0 Belt Integrated Starter Generator (BISG) systems with very limited battery capacity. They were primarily introduced to increase the smoothness and reliability (compared to 12V) of start-stop systems with a very limited electric torque assist and regenerative braking. Integration of a BISG requires no modification to the engine making it attractive. They have limitations on maximum torque (due to the belt drive) and any electric assist or regen braking is diminished by the engine friction. They are becoming ubiquitous in Europe given the tough CO2 legislation and the fact that the vehicles are a lot smaller. Even with their limitations, P0 systems can provide modest GHG performance and fuel economy gains. The P0 system on the Ram 1500 with the 5.7-liter V8 engine has a max torque and power rating of 130 lb-ft and 12kW with a battery capacity of 0.43kWh. It improves the fuel economy from 17.90/ 31.35/ 22.18 to 20.80/ 21.95/ 24.68 an improvement of 16.2/ 1.9/ 11.2% respectively.

P1 Crank Integrated Starter Generator (CISG) systems mounted on the output shaft of the engine are not limited by the belt drive of a P0 system and can have higher torque and power rating. The CISG system on the Mercedes M256 inline-six supplied by Mitsubishi Heavy Industries (MHI) has a power and torque rating of 184 lb-ft and 15.7 kW with a battery capacity of 1kWh. M256 has a 48 -Volt electric supercharger giving additional efficiency benefits (transient response, larger turbine – higher peak power and lower backpressure, low-end torque, knock resistance, etc.). The CISG systems need an expensive large-diameter low-speed motor since it is connected to the crankshaft without a reduction ratio.

New generation 48-volt systems available from multiple Tier-1 suppliers have a power output of up to 30kW. They have small high-speed motors that keep motor costs down and can be integrated into a vehicle in the off-axis P2 or P4 [Figure 16] configuration. In small/ midsize vehicles, such systems can provide capabilities that are comparable to a full hybrid system without the added cost and complexity of a high voltage system. The 30kW 48-Volt hybrid system from Continental integrated into a Ford Focus test vehicle can power the vehicle to an electric-only cruise speed of 50 mph [58]. The "Final Regulatory Impact Analysis - for the model Year 2021 – 2026 Passenger Cars and Light Trucks", March 2020, only considered a 48V BISG mild hybrid system with a motor power output of 10kW and a 0.403 kWh battery capacity down from the 0.806 kWh pack used in the NPRM analysis. It also completely ignored CISG systems (which are already in production) and also did not consider 48V P2, P3, and P4 systems as viable future technologies.



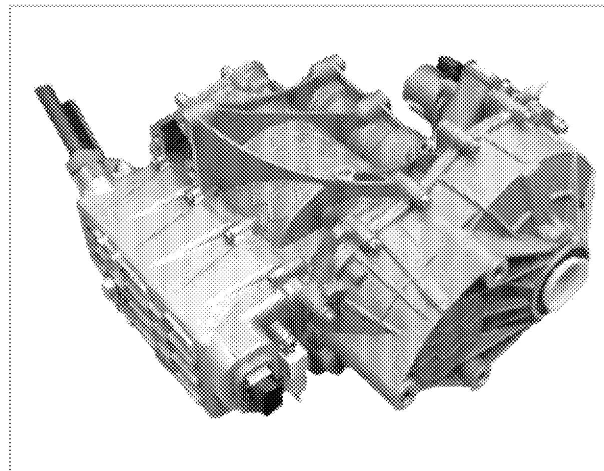


Figure 16: 48V off-axis hybrid module (Borg warner), 48V 35kW P4 e-axle (Magna)

7.0 Gasoline Engine for Hybrid Vehicles

Hybrid vehicles comprised 7% of the light-duty vehicle sales in 2020. They provide significantly higher fuel economy, in many cases 30-40% over the same vehicle platform with a conventional gasoline engine powertrain, sufficient to exceed the 2025 CAFE fuel economy requirement for the vehicle's footprint. Figure 17 illustrates the naming convention of the hybrid system based on the position of the electric motor. Few proprietary hybrid architectures in production do not fall into one of the categories shown below.

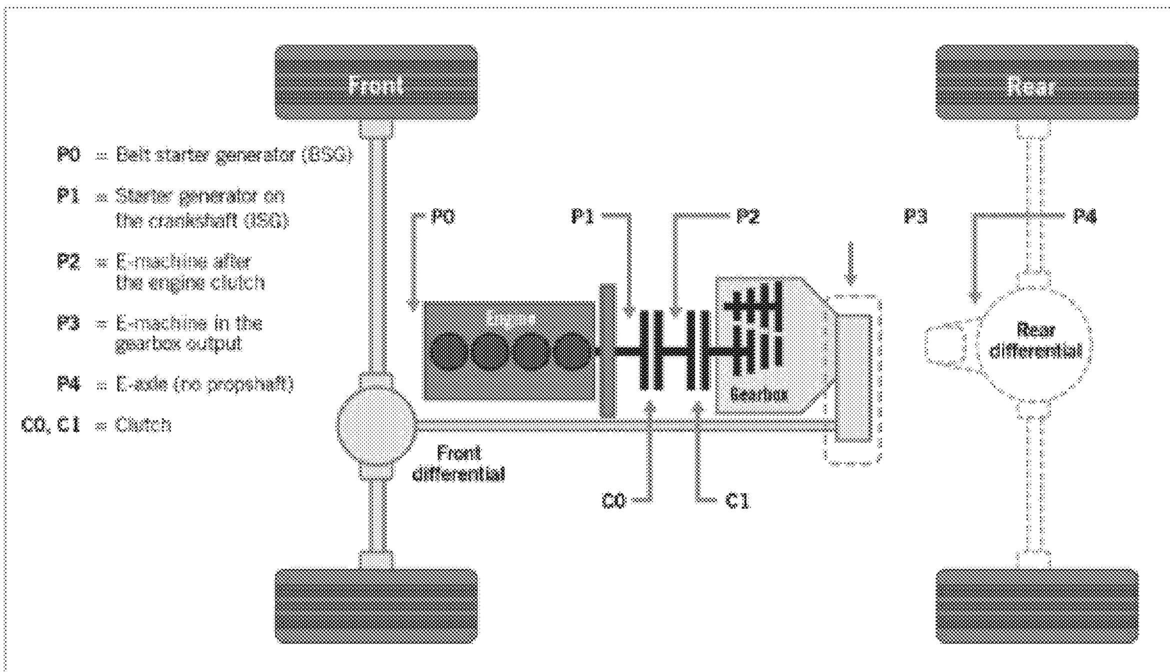


Figure 17: Hybrid system architectures specified by motor position [57]

Figure 18 shows how the level of electrification affects engine operating points. As the level of electrification increases, the engine operating points can be decoupled from the driver pedal (torque) request. The hybrid system is used as an energy management tool enabling the engine to spend more time in a narrow speed load range close to the peak efficiency points.

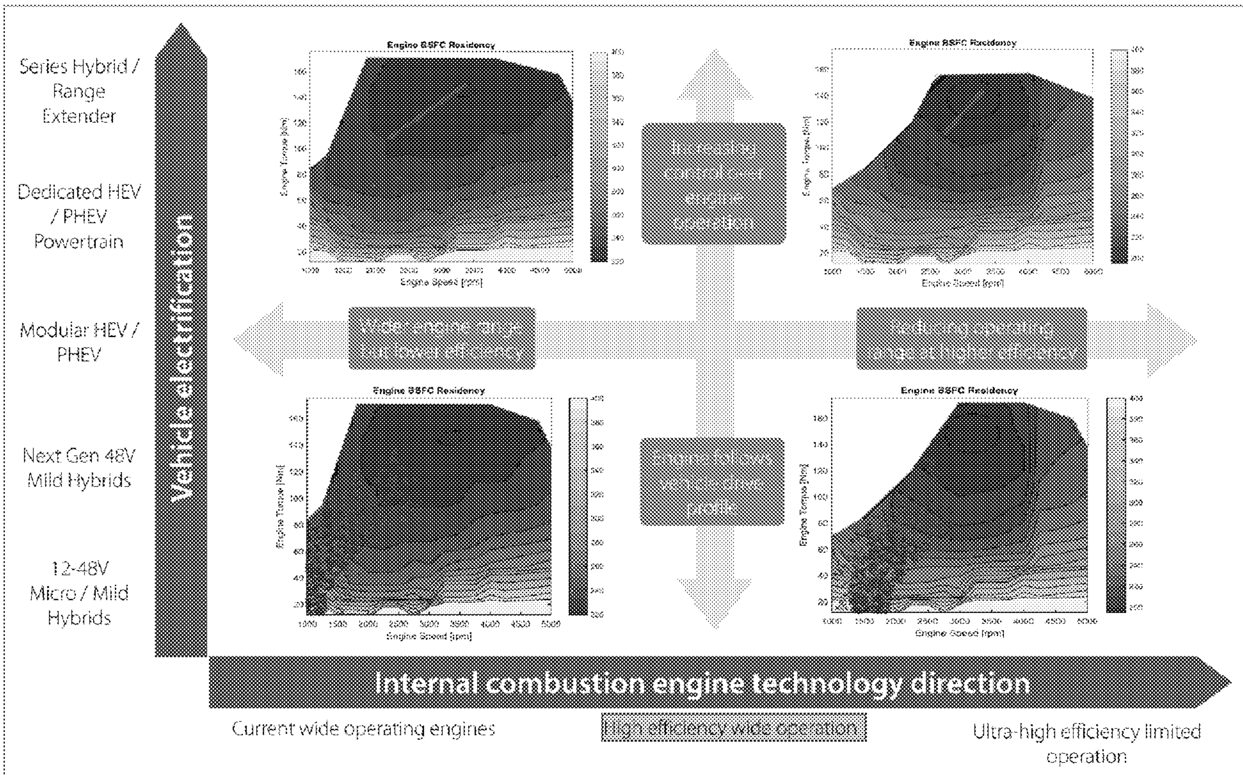


Figure 18: Powertrain optimization enabled by increasing level hybridization [78]

7.1 Naturally Aspirated Engines for Hybrid Powertrains

Hybrid powertrains enable engine operation in a very narrow speed load range which allows for the engine to be highly optimized. Most hybrid vehicles especially in the small and midsize economy segment will continue to use gasoline NA engines because of their cost-effectiveness. The formula for the state-of-the-art engine for this application has converged to an Atkinson cycle engine with a high compression ratio of about 14, a high cEGR rate of about 25% and a combination of increased in-cylinder turbulence and high energy spark plugs to ensure consistent ignition and fast burn rates.

Figure 19 illustrates Honda's "Sport i-MMD" system that operates in a series hybrid mode at low speeds and the engine driving the wheels directly through a fixed gear ratio at highway speeds. The 2-liter NA Atkinson cycle engine has a high compression ratio of 13.5, a maximum cEGR rate of 23%, and a maximum thermal efficiency of 40.6%. Figure 19 also shows the narrow speed load range in which the engine operates. This engine is very similar to the Toyota A25A-FXS used in the Toyota Camry Hybrid and RAV4 Hybrid that has a CR of 14:1, a high rate of cooled EGR, a high energy dual coil offset ignition system, and a peak brake thermal efficiency of 41%. The non-Hybrid version of the Toyota A25-FXS, the A25-FKS has a compression ratio of 13:1 and a peak BTE of 39%. Being part of the hybrid powertrain, the engine can be optimized to operate in a limited speed load range, higher compression ratio, etc.

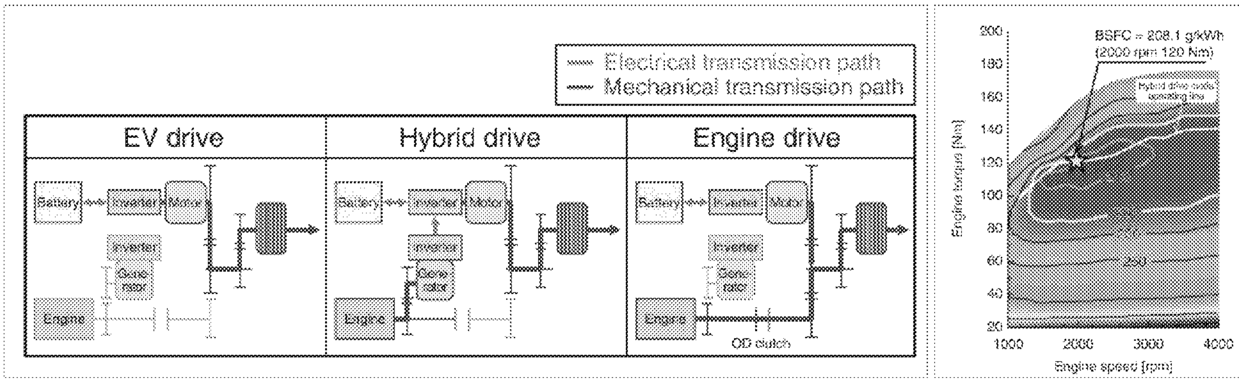


Figure 19: Honda Sport i-MMD hybrid system in the 2018+ Accord (left) and the BSFC map of the 2.0L engine

Increasing engine efficiency further will need higher cEGR dilution or air dilution with λ>2 (to keep engine-out NOx emissions low). This will require high-energy ignition systems like prechamber, plasma, or microwave, adding hydrogen-rich reformate gas to enhance combustion or advanced compression ignition.

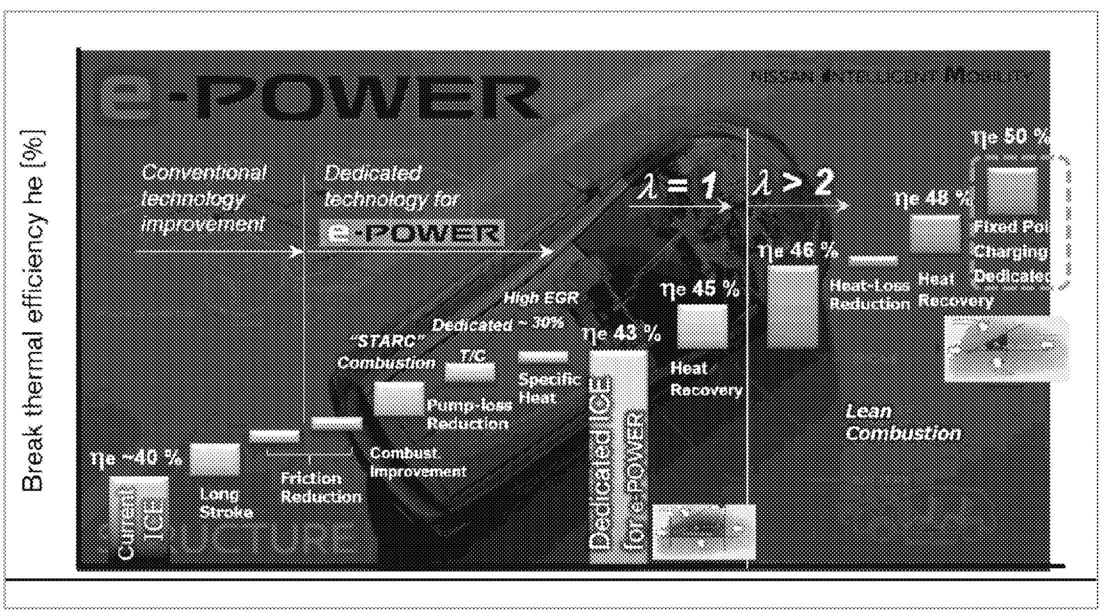


Figure 20: Technologies used in the gasoline engine used in the Nissan Note "e-power" series hybrid

Purely series-hybrid light-duty production vehicles have been rare. On the one hand, the decoupling of the engine from the driver torque demand enables a highly optimized engine that operates in a very small speed load range but the inefficiencies of converting mechanical work of the engine to electricity and then back to mechanical power to the wheels (through the electric motor) introduce inefficiencies. The 2021 Nissan Note (Japanese market) has a series-hybrid powertrain with the engine is optimized to operate at a single point achieving a brake thermal efficiency of 50%. Figure 20 shows all the technologies that Nissan employed to get to the target BTE [55]. The engine employs lean-burn combustion with lambda > 2 which keeps peak combustion temperatures and engine-out NOx emission low enough to negate the need for

NOx aftertreatment in the Japanese market. The stable combustion and acceptable burn rates of the dilute mixture are achieved by using production spark plugs by highly optimizing the in-cylinder charge motion and its interaction with the spark for a single operating point. Such an engine might require an SCR system to meet the US 2025 fleet average NMOG+NOx limit of 30 mg/ mile (Tier 3 Bin 30). If it does, the added complexity and cost will make them unattractive for volume production in the US.

7.2 Turbocharged Engines for Hybrid Powertrains

The use of turbocharged engines as a part of the hybrid powertrain is more prevalent in large vehicles and the luxury segment because of the higher power output targets and the ability to absorb the extra cost of a turbocharged engine. With tightening greenhouse gas and fuel economy standards, the use of a turbocharged engine as a part of a hybrid powertrain will expand to more vehicle segments.

Hybrid powertrains can keep the engine operating points in a small speed load range close to the peak efficiency island of the engine operating map. The supplemental electric motor torque decouples the engine torque output from the driver reducing the transient torque response of the engine. Also, the engine does not have to operate in the knock-limited low-speed high load region of the engine map [green area Figure 21]. Hence the turbine can be upsized, and the compression ratio of the engine can be higher. Flow volumes like EGR coolers, intercoolers, etc. can be optimized for higher effectiveness and engine efficiency since the torque response requirement of the engine is lower (larger volumes – more filling, emptying, pressurizing time). Further increase in engine efficiency will require increased EGR dilution which will need a high-energy ignition system like corona or a prechamber ignition system.

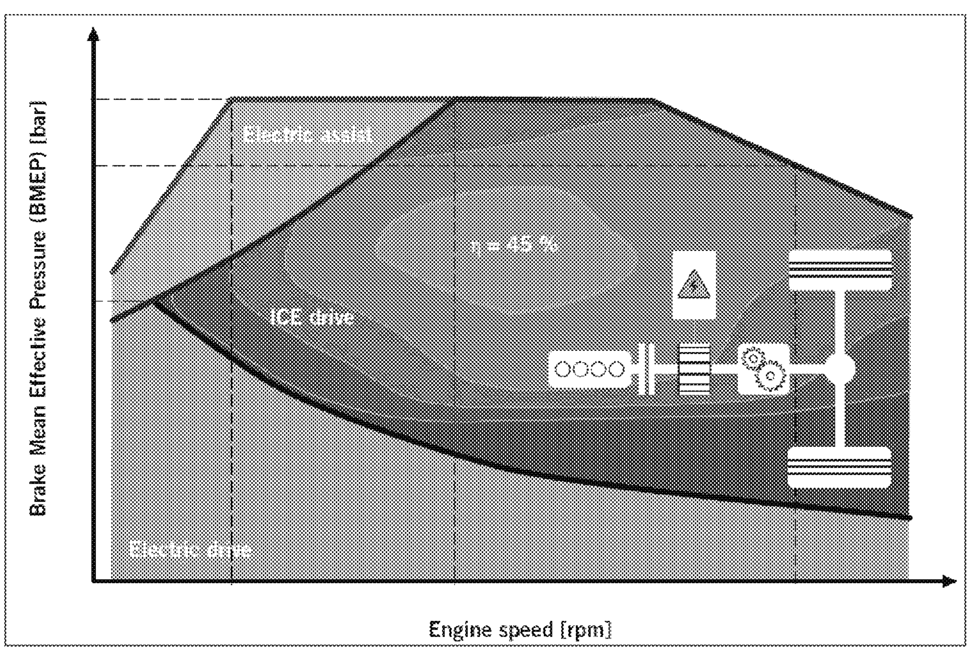


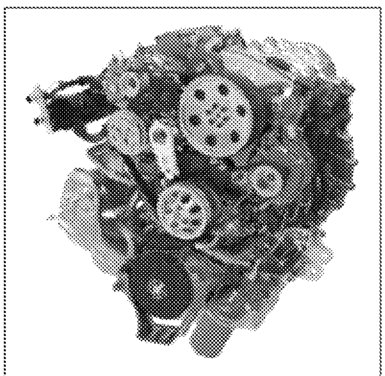
Figure 21: Combustion engine operating range in the hybrid powertrain, [54]

8.0 Alternative Engine Architectures

8.1 Opposed Piston Engine

Few companies are working to develop two-stroke opposed-piston engines (OPE) as an alternative to four-stroke engine engines for the light and medium-duty segment. Achates has demonstrated a working prototype 2.7-liter 3 cylinder opposed piston diesel engine in a Ford F150. The dimensions of the engine make it possible to be used in pickup trucks, full-size SUVs, and medium-duty commercial vehicles.

Figure 22 shows the comparison of 2.7-liter Achates Opposed Piston Engine with a 4-stroke diesel engine. The OPE has a significantly higher stroke to bore ratio and low surface to volume ratio



Engine	Conventional	OP Engine
Cylinders	6	3
Trapped Volume/Cylinder	1.0L	**1.6L**
Stroke/Bore Ratio	1.1	**2.2**
Trapped Compression Ratio	15:1	15:1
Combustion Chamber Surface Area/Volume (mm^{-1})	0.28	**0.18**

Figure 22: Achates 2.7-liter engine (left) and comparison with a 4-stroke diesel (right) [82,83]

The engine returned a CAFE combined unadjusted fuel economy number of 37 MPG in a (2015-2020) Ford F150 super crew [82]. A 2020 Ford F150 equipped with the 3-liter V6 turbocharged diesel engine achieved a (CAFE combined unadjusted) fuel economy of 31mpg (fueleconomy.gov). The opposed piston engine provides a fuel economy improvement of over 19%. More importantly, this is higher than the 2025 CAFE CHG performance and fuel economy target for the F150 based on vehicle footprint. Hence the vehicle can be used to offset other vehicles that cannot comply. The market share of diesel engines in the full-size pickup and SUV segment in the US was about 0.6% in 2019 and 1% in 2020. The corresponding market share in classes 2 and 3 was 2.2% in 2019 and 3.4% in 2020. Hence diesel engines make up a very small portion of the light-duty segment and medium-duty classes 2 and 3. This is largely in part due to the higher cost, complexity, and warranty requirements of the aftertreatment system required to meet the NOx standards in the US. This cost will go up further with the full phase-in of the 2025 Fleet average NMOG+NOx limit of 30 mg/ mile (Tier 3 Bin 30).

To reach production, any new engine architecture will have to overcome the following challenges:

1. Prove significant efficiency improvement
2. Have competitive costs
3. Meet emission standards
4. Prove reliability

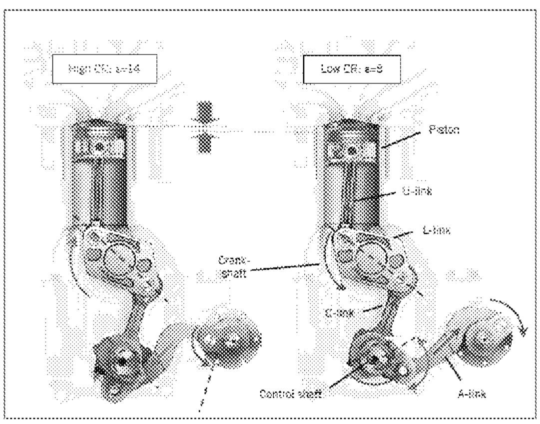
5. Win a major OEM commitment
6. Win consumer acceptance

Achates have shown that the OPE meets the first two criteria. There are still significant challenges to be overcome before the engine reaches production. The extremely small market share of diesel engines in the full-size pickup and SUV segment makes these challenges even bigger.

8.2 Variable Compression Ratio (VCR) Engines

The theoretical efficiency of an engine is increased by increasing the compression ratio. At low loads when the engine is not knock limited, increasing the compression ratio increases combustion stability and brake thermal efficiency. But a high compression ratio limits the maximum BMEP of an engine due to knocking. Higher BMEP will require increased spark retard causing lower efficiency and higher exhaust temperatures (requiring fuel enrichment for cooling the charge to prevent knocking and lowering exhaust temperatures for component protection). For turbocharged engines knocking limits the degree of downsizing limiting its potential as a fuel-saving strategy.

Nissan put into production the world's first VCR engine, the KR20DDET (2.0 liter, 4-cylinder, DI, Turbo) in 2017. Figure 23 (left) shows the multilink system that enables the compression ratio to be varied between 8 and 14 depending on the speed and load of the engine (right).



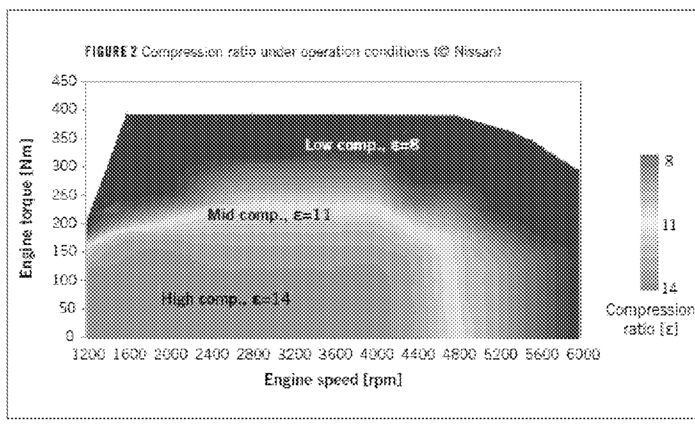


Figure 23: Multilink mechanism of the Nissan VCR (left), CR under operating conditions (right), Nissan [80]

At combustion TDC (and expansion stroke), the angle of the connecting roof with the axis of the cylinder bore lower compared to that of a conventional engine reducing the side thrust pressure between the piston and cylinder [80, 81] reducing friction. This compensates for the increased friction due to the extra bearings of the VCR linkage [80]. The net engine friction of the VCR engine is marginally lower than the V6 NA engine it replaced (Figure 24).

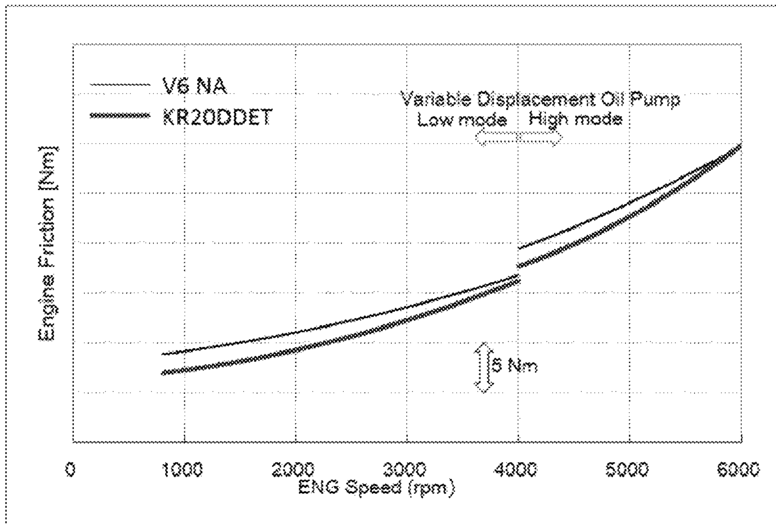


Figure 24: Engine friction KR20DDET VCR engine compared to the VQ37VHR V6 engine

The real-life efficiency gain due to the VCR system was limited by the Increased cooling losses due to the higher combustion temperatures and surface to volume ratio (at high CR) of the combustion chamber at low loads. The high compression ratio required deeper valve clearance recesses on the piston increasing the cooling losses further. It is possible to reduce the heat transfer losses with an optimized engine design with a lower bore to stroke ratio (section 3.4).

Many suppliers are working on methods to implementing variable compression ratios in engines. Figure 25 shows two VCR connecting rod concepts from FEV and AVL.

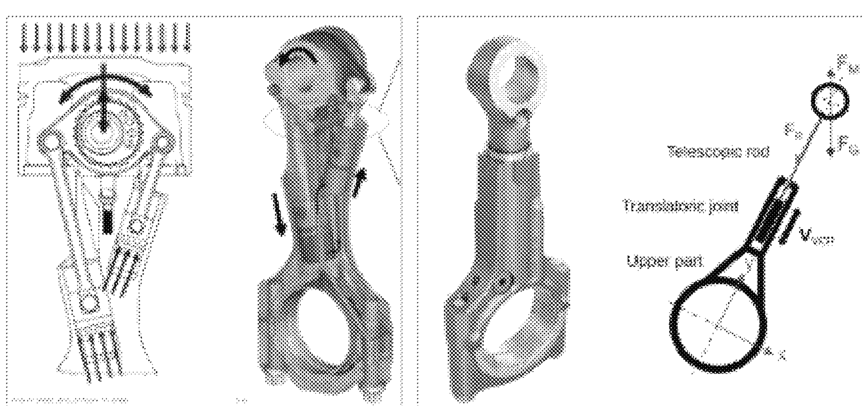


Figure 25: VCR connecting rod concepts from FEV (left) and AVL (right)

Though the VCR system can theoretically increase the efficiency of the engine, it adds cost and complexity. There are significant R&D costs, manufacturing and component costs, cost of licensing the technology, and complexity of calibrating the engine. Due to these factors, Roush does not see high penetration of VCR systems in the light-duty market in the 2025-2035 timeframe.

9.0 Boosting Systems

An ideal boosting system has the following characteristics:

1. Produce the target intake pressure for the minimum exhaust backpressure - high efficiency
2. Get to steady-state boost condition in minimum time during a driver tip-in - low turbo lag
3. Minimize other parasitic losses on the engine

In a turbocharged engine (with a wastegated turbocharger), the turbine is sized for the "torque knee" point i.e., the highest torque at low rpm (Figure 26). Smaller the turbine, the better the transient response but the higher the backpressure over most of the engine map (points where the wastegate is open) hurting engine efficiency. A larger turbine results in reduced back pressure and increased efficiency at the cost of low-end torque and transient response.

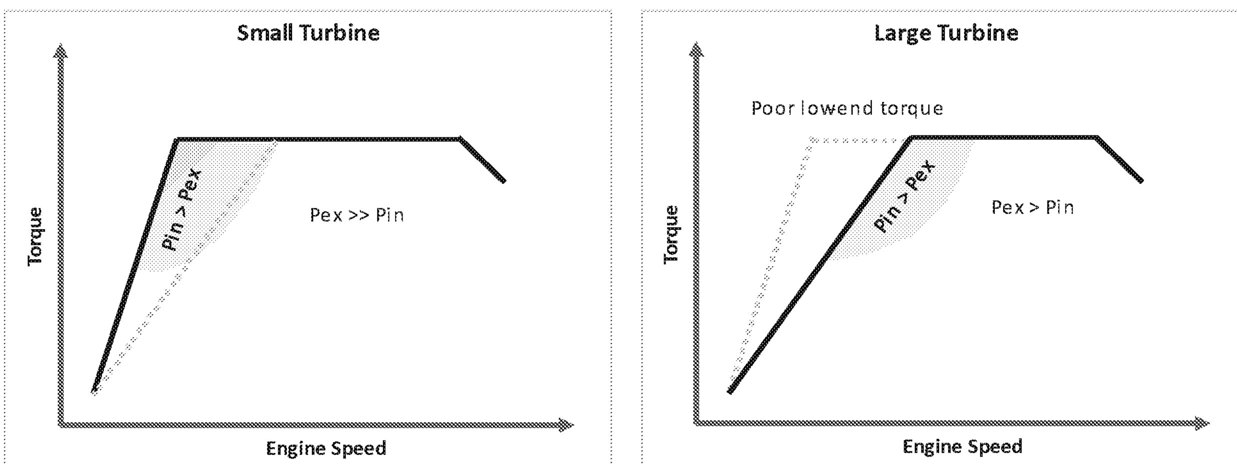


Figure 26: Effect of turbine size on engine torque curve and backpressure

9.1 Turbocharger with Variable Geometry Turbine (VGT)

A VGT is analogous to having a different size turbine for each actuator position. The vanes can be closed for high low-end torque or open for minimum backpressure or maximum top-end power. It produces the required intake manifold pressure with lower exhaust backpressure and reduces turbo lag when compared to a wastegated turbocharger

Porsche introduced gasoline VGT is the 2006 911 turbo with two BorgWarner BV50 pivoting vane VGTs. The turbines on these turbochargers could tolerate exhaust temperatures of 1050°C. To achieve this temperature tolerance, Inconel 617 needed to be used for the VGT mechanism. Increasingly gasoline VGTs have been introduced in smaller gasoline engines for budget applications (VW EA 211 EVO 1.5) with comparable solutions available from all major turbocharger suppliers.

VGTs are an enabling technology for Miller cycle engines. The increased turbine efficiency of VGTs enables them to produce the required boost pressure at the lower exhaust gas temperatures (enthalpy) of a Miller cycle engine. The low exhaust gas temperature also means that the VGT mechanism is not subjected to the extreme temperature of normal turbo gasoline engines.

9.2 Turbo + Electric Superchargers and Electric Assisted Turbocharging

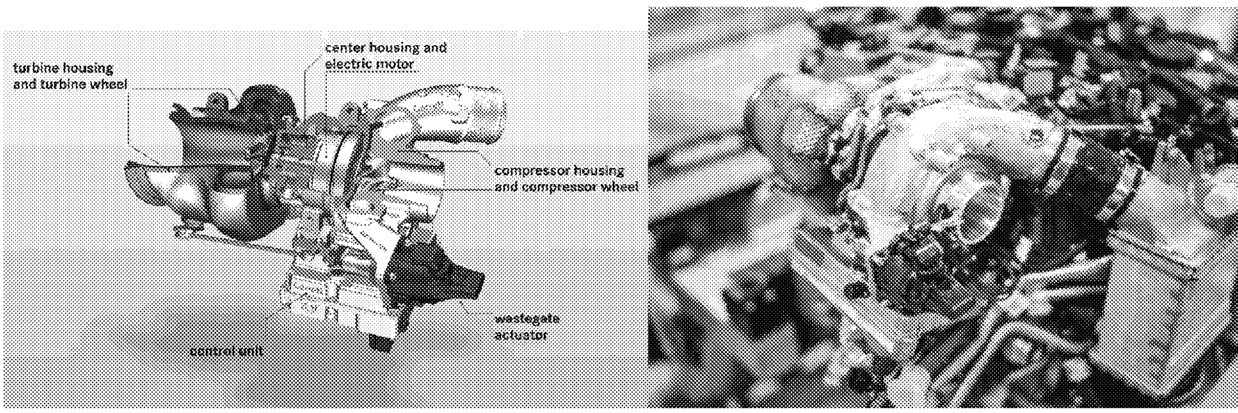


Figure 27: Garrett eTurbo, Source: Mercedes Benz (2022 in the Mercedes Benz C63)

Both these technologies work with a 48V mild-hybrid system to meet the power requirements of the high-speed electric motor. With the Turbo + electric supercharger (production SI engines - Mercedes Benz M256, Jaguar Land Rover AJ300; Table 4), the supercharger is added downstream of the turbo compressor in the air path. With an electric-assisted turbocharger [Figure 27], an electric motor is added to the shaft of the turbocharger. These systems have the following advantages

- The turbocharger turbine can be upsized. This reduces the back pressure and increases average engine efficiency across the operating map.
- The lower back pressure and reduced internal residuals resulting from the larger turbine reduces the knock propensity of the engine at high loads enabling the increase of compression ratio.
- The ability to create a positive delta pressure difference (intake – exhaust) across the engine aids in scavenging reducing residuals and knock at the low-speed high load region of the engine map.
- Most systems from suppliers produce full boost from idle in about 200ms – reduced turbo-lag. This leads to better drivability and reduced shifting resulting in better NVH and a positive fuel efficiency benefit. This also enables down-speeding of the engine and decreased shift busyness increasing efficiency.

10.0 Dilute SI Operation by Increasing Mixture Reactivity

Research [47,48] has shown that adding a small amount of Hydrogen (H2) to intake change can significantly increase the EGR tolerance of an engine. The addition of 1% of H2 increased the EGR tolerance of a gasoline engine from 25% to 50%.

10.1 Non-Catalytic Dedicated In-Cylinder Reforming

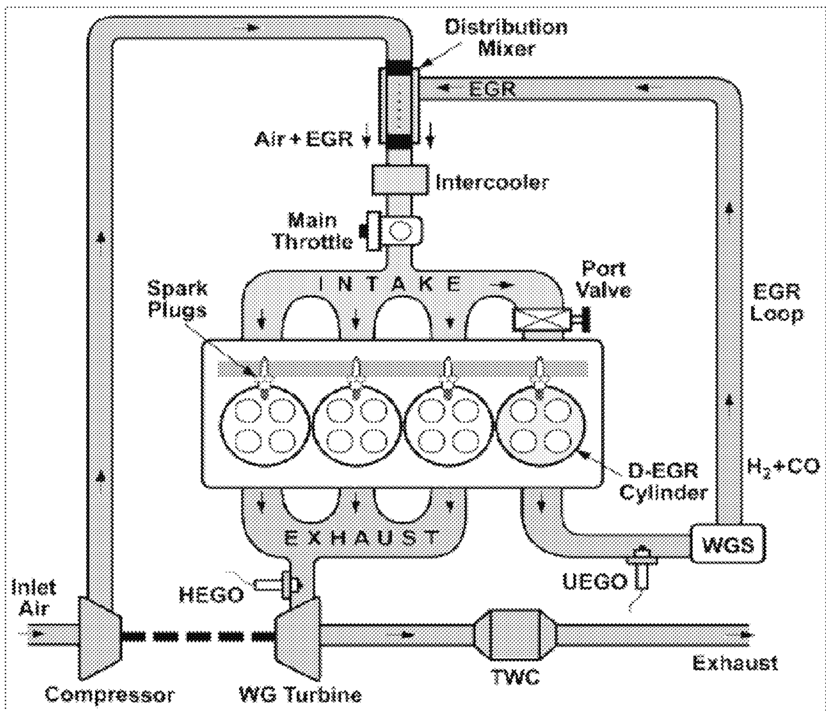


Figure 28: Dedicated EGR system SWRI

Figure 28 shows the dedicated EGR system developed by Southwest Research Institute (SWRI). One cylinder is converted to operate under fuel-rich conditions to produce reformate gas with high concentrations of H2 and CO. The reformate gas produced by this cylinder is routed to the intake of the remaining cylinders and consumed in SI combustion [10]. The SWRI D-EGR demonstration on a 2.4-liter PFI NA engine achieved a fuel consumption benefit of over 10% across the engine operating map. The technology-enabled the compression ratio to be raised from 10.5 to 14:1 and the peak thermal efficiency exceeded 42%. The technology added to a 2-liter DI turbocharged engine [9] enabled the increase of compression ratio from 9.3 to 11.7 and a BSFC reduction from 385 g/kwh (production engine) to 330 g/kWh at 2000 rpm 2 bar BMEP. The lowest BSFC decreased from 236 g/kWh to 212 g/kWh while the engine was able to reach a peak BMEP of 17 bar. A 2012 Buick Regal with the 2.0-liter turbocharged engine converted to use DEGR [11] achieved a fuel economy increase of 13% and 9% over city and highway driving while producing 31mg/ mile of NOx + NMOG, almost achieving a Tier 3 Bin 30 level of 30 mg/mile.

The DEGR system is a promising technology to achieve high fuel economy and reduced emissions due to the minimal change to the engine architecture and use of automotive components already in production and has reached technology maturity.

10.2 In-Cylinder Fuel Reforming by Injecting Fuel During Negative Valve Overlap (NVO)

Production engines like the Toyota A25A-FKS use NVO (Figure 29) [12] (closing exhaust valve before gas exchange TDC and opening Intake valve after gas exchange TDC) to increase internal residual in regions of the engine operating map that are not knock limited (low and mid loads and speeds). The internal residual reduces pumping work and helps combustion stability by increasing trapped charge temperature.

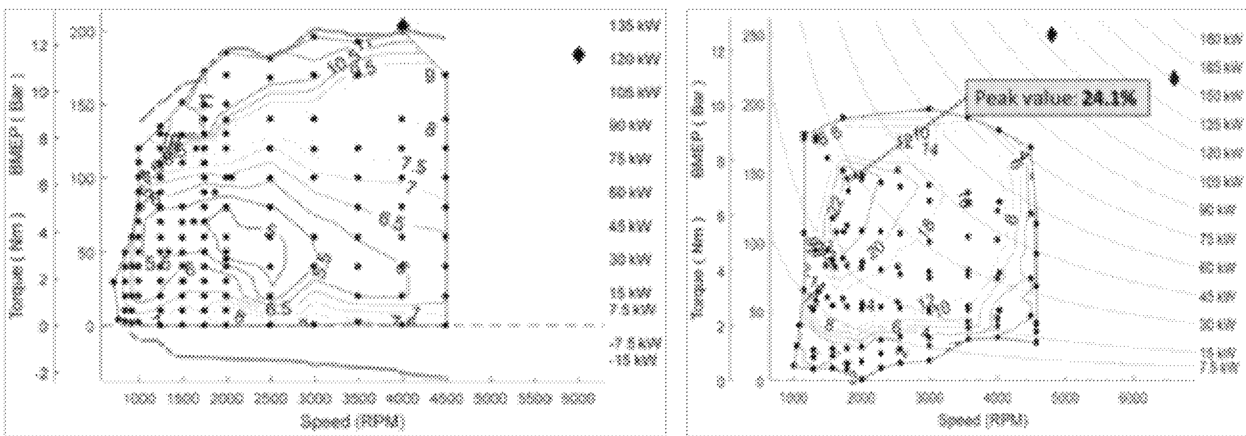


Figure 29: Valve overlap for the 2018 Toyota A25A-FKS (left) and cEGR rates (Right) [12]

A small pilot fuel injection during NVO can be used to alter the main-period fuel reactivity through in-cylinder reformation or partial oxidation of the injected fuel [13,15]. This reformate that contains H2 and CO can be used to increase the lean combustion limit of an EGR diluted engine. The technique applied to a production GM 2.0-liter turbocharged engine [14] enabled compression ratio to be increased from 9.25 to 11.7 and the use of 32% EGR (total i.e., internal residual + cooled EGR) at 1800 rpm and 3 bar BMEP before the COV of IMEP exceeded 4%. When compared to the production engine, the BSFC of the modified engine at 1800 rpm, 3 bar BMEP decreased from 358.3 g/kWh to 278.7 g/kWh, an improvement of 22%. The study [14] was only a part of the work detailed in [15] and the aim of the study was not to maximize the efficiency of an engine using fuel injection during NVO. More work needs to be done to study the potential of this technology.

Pilot fuel injection during NVO to improve dilution tolerance and brake thermal efficiency is an attractive technology since it requires no other engine hardware other than a cam-phasing mechanism with the required phasing authority and speed. This might require electric cam phasers, which are becoming increasingly common in light-duty applications.

10.3 Catalytic Exhaust Gas Recirculation-Loop Reforming

Figure 12 illustrates the schematic of a catalytic EGR system. One cylinder is operated at a lean air-fuel ratio and a secondary fuel injection is used post-combustion. The exhaust of this cylinder is passed over a catalyst bed. The resulting endothermic reaction produces reformate gas that is high in hydrogen [45,46].

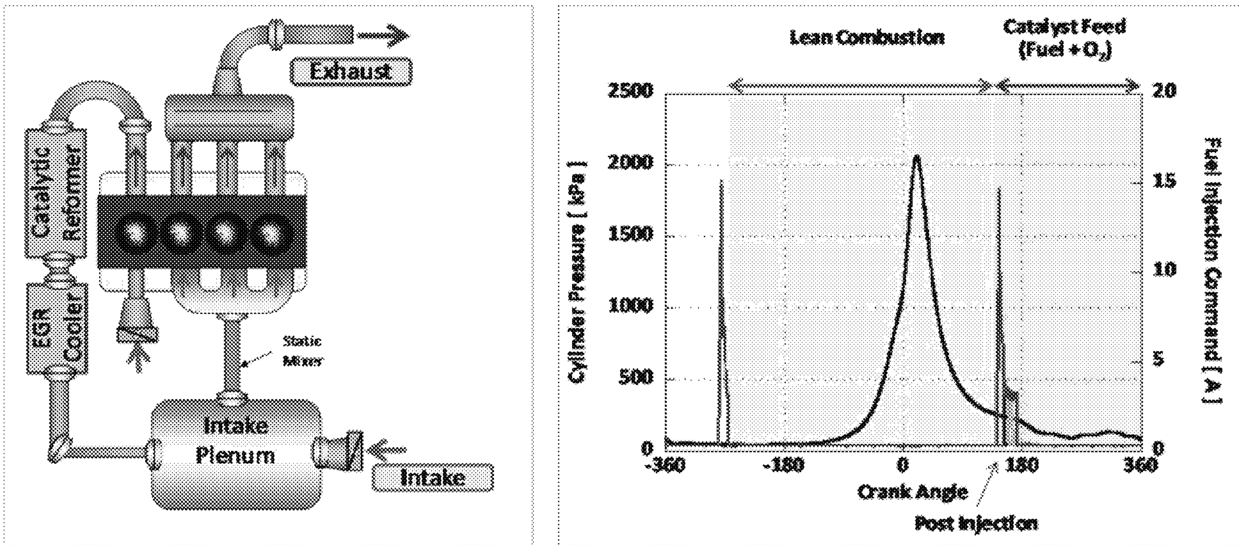


Figure 30: Catalytic EGR schematic (left), cylinder pressure, and fuel injection strategy for cylinder 4

In tests performed on a 2.0 L GM Ecotec LNF DI engine, at 2000 rpm 4 bar BMEP, the intake volume concentration of H2 of 5% was achieved. The EGR tolerance increased from under 25% to over 50% by volume. The efficiency of the engine improved by 8% over the baseline at the operating point. The large volume of the EGR loop makes it difficult to change intake manifold pressure (especially in turbocharged engines) during transients. A high-power 48-volt system with torque assist to the driveline and/or a (48V) electrically assisted boosting system can be used to overcome this.

11.0 High Energy Ignition Systems

Most high-efficiency combustion and engine concepts, gasoline, and diesel, involve burning the most dilute homogeneous charge with the highest burn rates possible while a) Maintaining ideal combustion phasing, b) Keeping peak pressure within engine design limits, and c) Keeping the pressure rise rate (or ringing index in the case of HCCI) below the NVH threshold.

All advanced combustion systems like HCCI, SACI, PCCI, RCCI are all trying to attain a high burn rate of a dilute mixture with compression ignition. The challenge of most of these concepts is the complexity of engine hardware/ control system and the narrow operating range (more suitable to hybrid powertrains) necessitating transition to conventional combustion outside this narrow operating range.

Figure 31 illustrates the different ignition systems that can be used in an SI engine.

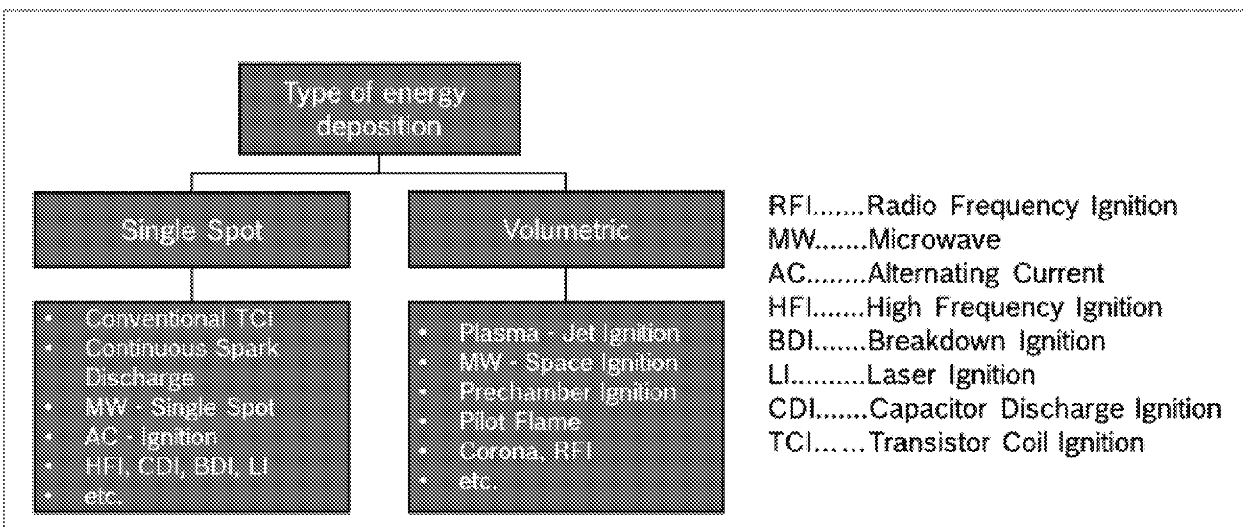


Figure 31: Different ignition systems [43]

High energy volume ignition systems have the following benefits:

1. Increase dilution limits- These systems produce multiple ignition sites in extremely dilute mixtures resulting in high burn rates and low cycle to cycle variation under such conditions. Increased EGR dilution results in higher brake thermal efficiencies
2. Enable combustion regimes like SACI- The ability to ignite dilute mixtures more consistently make them an enabler for combustion regimes like SACI extending the operating range [25,26]
3. Increase knock resistance - The fast burn rates make engines more knock resistant at high engine loads enabling a higher degree of downsizing/ higher compression ratios [25].

4. Enable valve strategies for higher Miller/ Atkinson ratios - State of the art NA and Turbocharged engines have been adopting Atkinson and Miller Cycles respectively as an effective means to increase brake thermal efficiency. The valve strategies have to be carefully optimized not only to expansion work (Atkinson/ Miller ratio - effective compression to effective expansion ratio) but also to maintain an acceptable value of in-cylinder turbulence to achieve high burn rates. With spark plugs, the right value of in-cylinder turbulence is required to maintain high burn rates. The addition of cooled EGR reduces the reactivity of the mixture, flame speed and further increases the burn duration. In high EGR engines, to keep burn durations in the acceptable window, the cylinder head, and piston design, valve lift, and timing, etc. have to be optimized for maximizing in-cylinder turbulence. This makes extreme Miller/ Atkinson ratios more difficult. Volume ignition systems reduce the reliance on in-cylinder turbulence and enabling valve timings to be optimized for miller/ Atkinson cycle and cylinder heads to be optimized for volumetric efficiency.

11.1 High Energy Spark Plugs

EGR dilution is a promising technology for increasing the efficiency of SI but Increasing the amount of EGR in an engine with a conventional spark plug increases the cycle-to-cycle variability through the following mechanisms

1. The increased dilution increases breakdown voltage [17].
2. Flame kernel growth is destabilized because a higher density of mixture shortens discharge duration [18].
3. Flame propagation is destabilized because an increase of inert gas decreases laminar burning velocity [19]

High market penetration of turbocharged engines and increased use of cooled EGR as a tool for improving engine efficiencies both in turbocharged and naturally aspirated engines have necessitated high energy spark plugs that can reduce cycle-to-cycle combustion variability (low COV-IMEP) and provide fast consistent 0-5% burn duration. The Toyota A25A-FKS uses a dual-coil offset ignition system along with other engine designs (to increase in-cylinder turbulence) and operation strategies (negative NVO – increased residuals) to attain a peak cooled EGR rate of 24%. Spark plugs that enable engine operation with increased dilution necessitate little/ no engine modifications and hence are a very attractive technology.

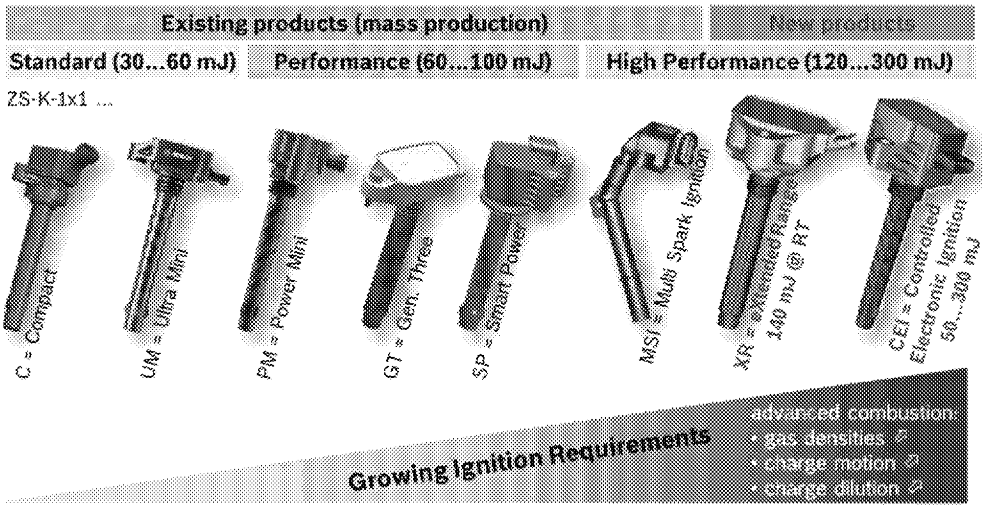
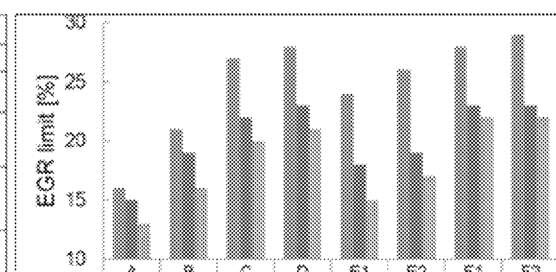


Figure 32: Bosch high energy spark plug roadmap [43]

[20] looked into different ignition coil specifications and their effect of EGR dilution limits for a 1.6-liter 4-cylinder turbocharged engine (CR 12:1, LP and HP cooled EGR loops) at the 3 engine operating points (3 bar IMEP at 1200, 2000, and 2800 rpm). Compared to the base spark plug, switching to a dual coil multi-spark with ignition energy of 300mJ almost doubled the EGR tolerance without any change to the engine (Figure 33). The combustion COV limit was 2% of IMEP, stricter than the 4% limit that most studies use.

No.	A	B	C	D	E1	E2	F1	F2
Specification	Single spark				Multi spark			
	Base	High energy	High energy	Dual	Single coil		Dual coil	
Sample								
Secondary energy* (Total)	70mJ	129mJ	123mJ	230mJ	145mJ 18times	151mJ 12times	280mJ	300mJ
Secondary current* (Peak)	60mA	50mA	130mA	220mA	140mA	140mA	130mA	130mA
Spark duration* (Total)	1.8msec	4.3ms	1.8msec	1.7msec	3.5msec	3.7msec	2.8msec	3.0msec



	A	B	C	D	E1	E2	F1	F2
1200rpm	16	21	27	28	24	26	28	29
2000rpm	15	19	22	23	18	19	23	23
2800rpm	13	16	20	21	15	17	22	22

Figure 33: Different ignition coil specifications and EGR limit results [20]

Figure 34 (from [20]) shows the relationship between the EGR limit and secondary energy. An increase of secondary energy increased the EGR limit at all engine speeds. Figure 34 also shows the BSFC of the engine and the energy consumed by the various ignition systems. Even after accounting for the high energy consumption of the ignition systems, there was a significant decrease in BSFC. Figure 34 also illustrates the synergies that can be achieved by using a 48-volt mild hybrid system in a vehicle equipped with a high-energy ignition system. More of the energy requirement for ignition can be met with energy recovered during regenerative braking.

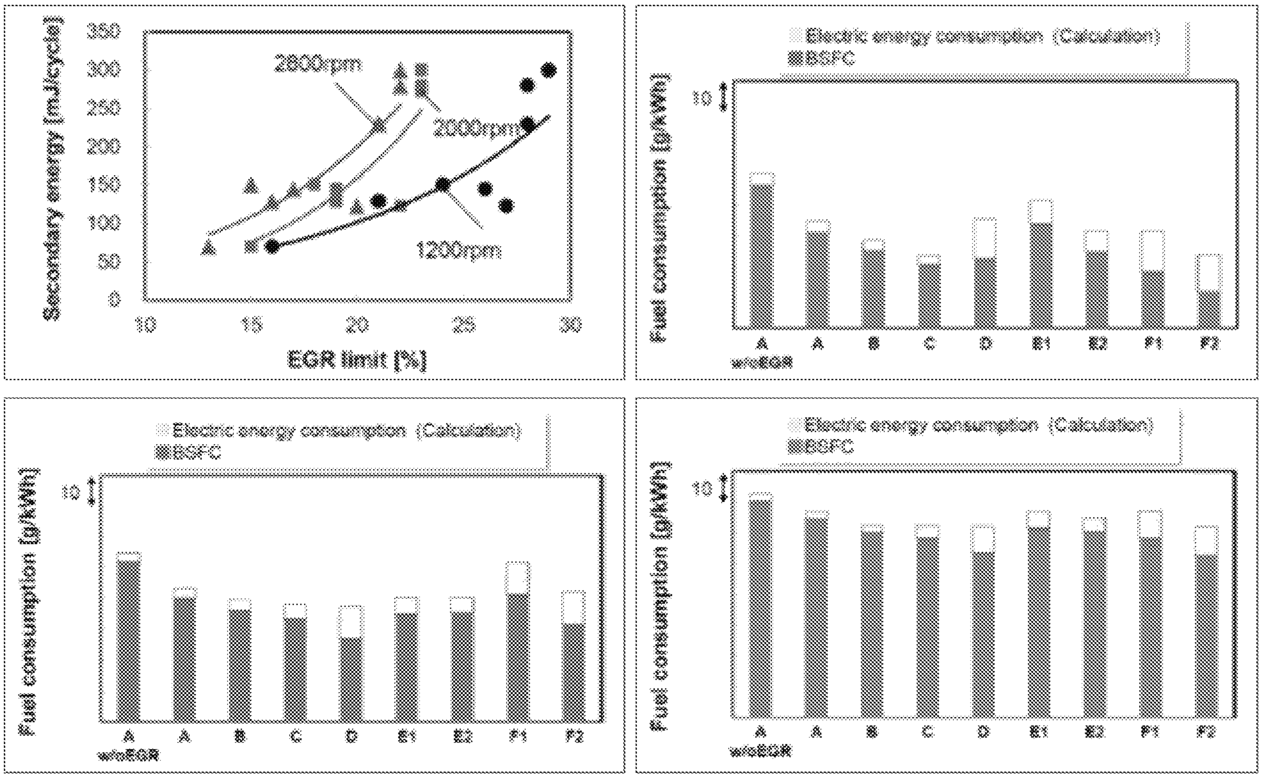


Figure 34: the (top left) relationship between EGR limit and secondary ignition energy, Engine BSFC and calculated electric energy consumption (1200 rpm – grey, 2000 rpm blue, and 3000 rpm – green) load 3 bar IMEP

11.2 Alternative spark plug designs

Alternative spark plug designs like a three-pole park igniter studied in [21, 22] broaden the ignition area and extends the lean operating limit, shortens the 0-5% burn duration (faster flame kernel development), faster 0-50% burn time, and lower cycle to cycle variation (COV IMEP).

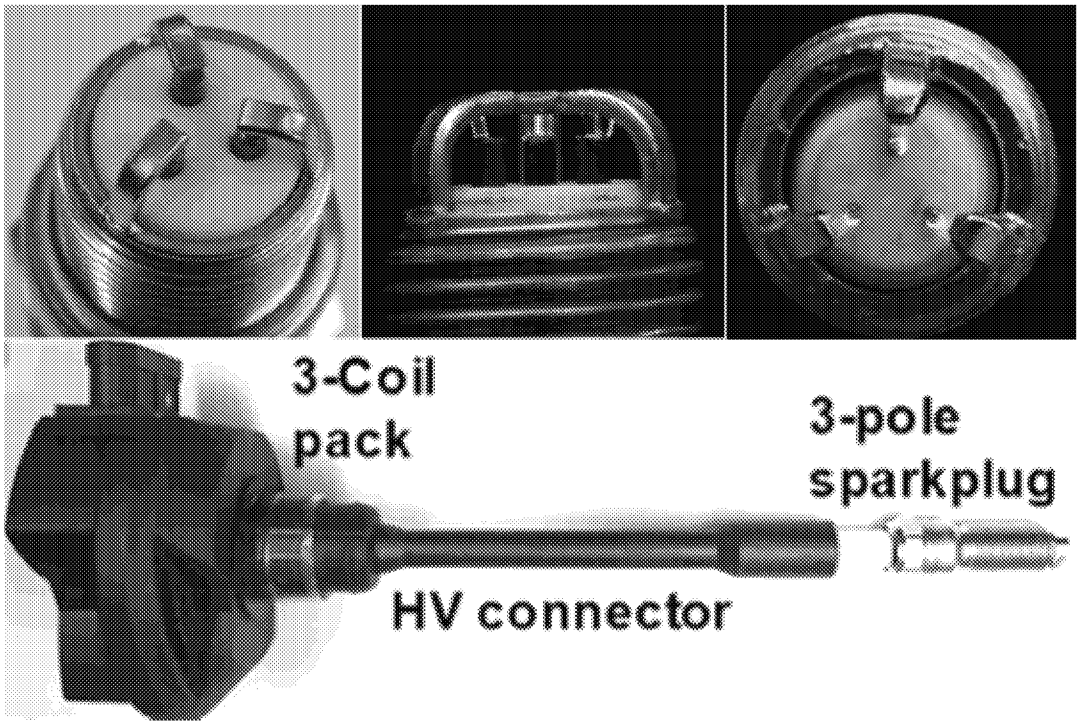


Figure 35: 3 pole spark plug design [21,22]

The three-pole spark plug was installed in a Ford 6.2-liter V8 engine [22] and operated in a single-cylinder mode to study the improvement in the dilution limit (air dilution) over a high energy single pole plug. Engine test results showed that the multipole pug was most effective when the intake charge was at the boundary of the lean/dilution limit. The configuration achieved an indicated thermal efficiency improvement of 5% at 2.6 bar IMEP at 1500 rpm under high EGR dilution when compared to using a single-pole spark plug.

11.3 Corona Ignition Systems

Corona ignition systems can be divided into four broad groups: arc design, steamer design, barrier discharge design, and pulse design [52]. A detailed discussion of the benefits and drawbacks of the different systems is beyond the scope of this report. Corona ignition systems have shown significant improvement over conventional spark ignition in faster combustion and increased tolerance to EGR and air dilution.

A study by BMW [51] compared the ability of three ignition systems below to operate under increased cooled EGR dilution:

- 100mJ Transistor Coil Spark Ignition (TCI).
- An Advanced Spark Ignition System (ASI) with the ability to vary the secondary current during the spark discharge both in current strength and current duration. Figure 36
- A Radio Frequency Corona Ignition system (streamer design)

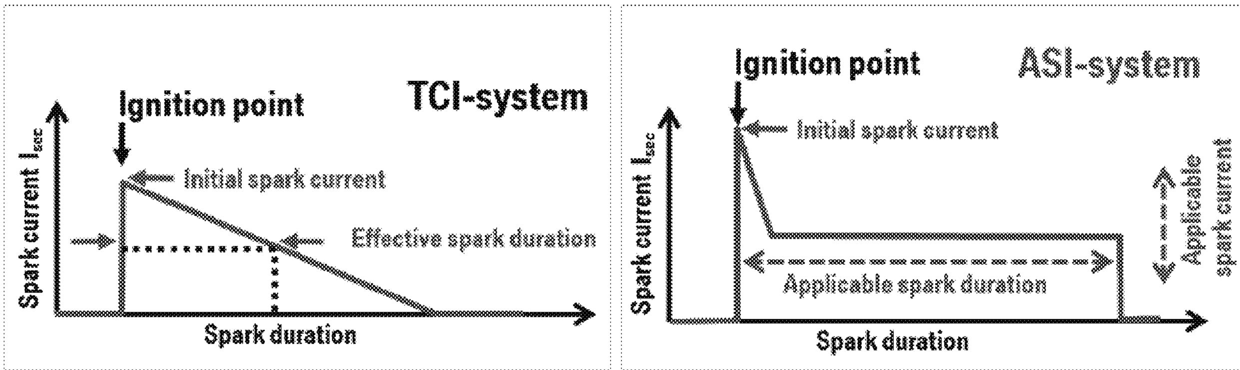


Figure 36: Characteristics of a single-coil spark discharge (TCI, left) and a spark discharge obtained by an advanced spark ignition system (ASI, right) [51]

The study was conducted on BMW's new generation (2016 -) of turbocharged engines with dual VCT and variable lift intake system. The piston design was optimized for both, corona ignition (prevent arcing at low loads) as well as charge motion.

Figure 37 illustrates these correlations by depicting the burn delay statistics as a function of the 5–50 % MFB burn duration for all three ignition systems. The different points correspond to different intake lift phasing and exhaust timings and different internal residuals. TCI and ASI become unstable for longer main combustion durations. With Corona we see almost no scattering indicating the ability to provide an extremely stable start of combustion.

Figure 38 shows the cooled EGR tolerance for three ignition systems. At low loads, the Corona Ignition system has a significantly higher tolerance of cooled EGR before hitting the COV of IMEP limit of 3%.

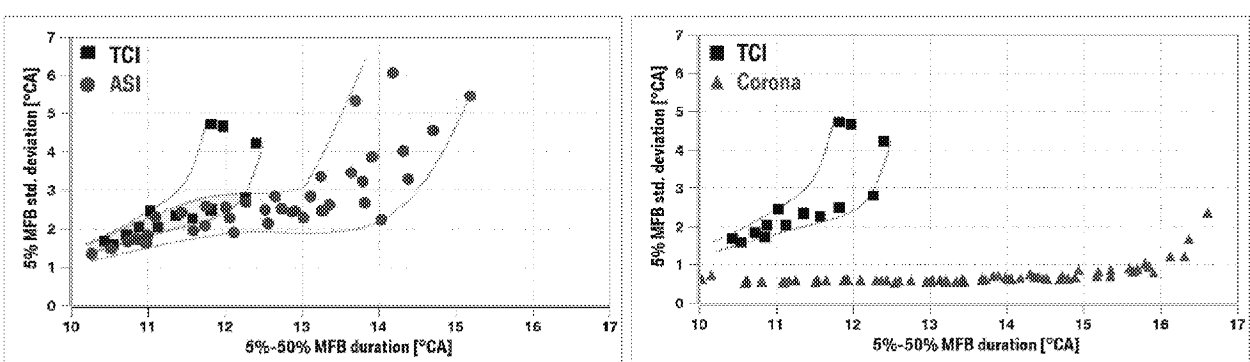


Figure 37:Standard deviation of the 5 % MBF (1000 rpm, IMEP = 1 bar, CR = 12). [51]

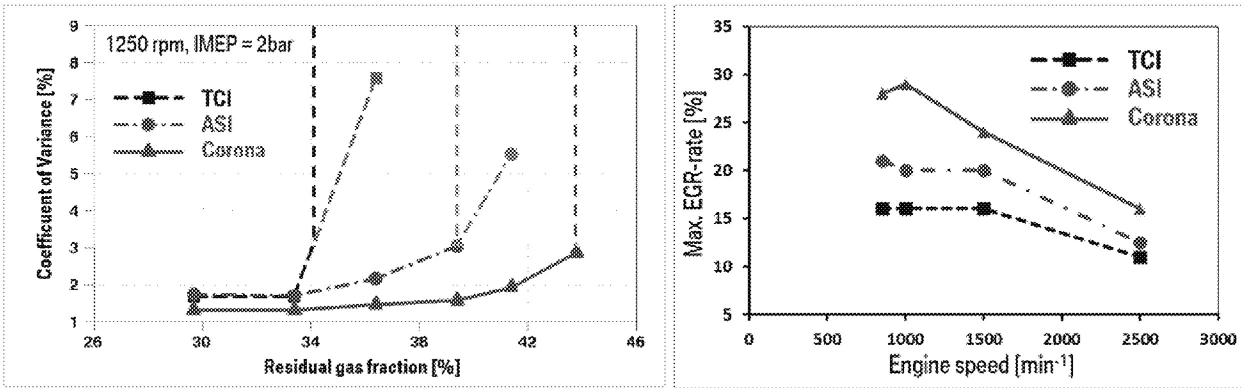


Figure 38: Left: Engine smoothness as a function of the internal residual gas rate (1250 rpm, IMEP= 2 bar, CR = 12). Right: Comparison of the maximal tolerable EGR-Rate as a function of engine speed (IMEP = 0.8 bar). [51]

[25] studied the effect of using a low-temperature plasma groundless barrier discharge igniter (GBDI) in supporting flame assisted (compression ignition/) Low-Temperature Combustion (LTC). The ignitor was able to extend the EGR diluted flame assisted LTC range due to the ability to ignite very dilute mixtures (compared to a spark plug).

11.4 Prechamber Jet Ignition Systems

Prechamber ignition systems are one of the most widely researched areas today as a potential technology for enabling the next generation of high efficiency (42-48%) lean-burn engines with lambda greater than two and engine-out NOx emissions below the threshold requiring any NOx aftertreatment to meet emission norms. [62,63, 64, 65,66, 67, 68, 69] (also see Figure 3)

The system consists of a small prechamber (3 to 5% of clearance volume) connected to the main combustion chamber by a series of small orifices. The combustion is initiated in the prechamber using a spark plug causing the burning mixture to travel at high velocity through the orifices into the main chamber. The high velocity extinguishes the flame and seeds the main chamber with active radical species that reignite some distance away from the pre-chamber. A large number of ignition sites in the main chamber enables burning extremely dilute (air or cEGR diluted) mixtures at high burn rates.

Figure 39 illustrates the different types of prechamber ignition systems.

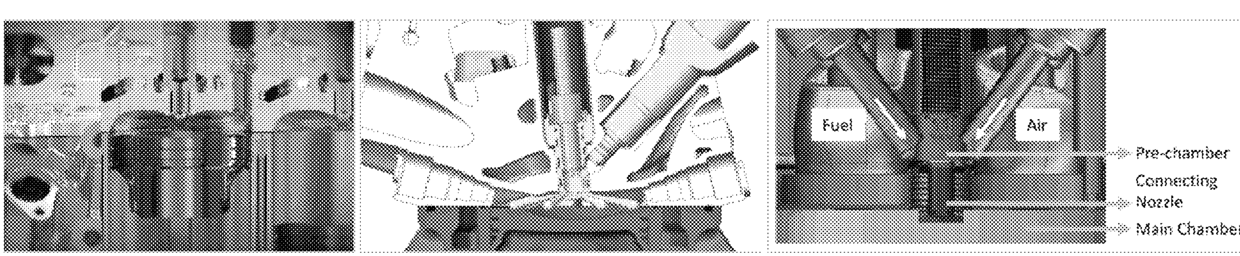


Figure 39: Types of prechamber ignition systems

- Passive prechamber ignition (Figure 39, left) – The prechamber has a sparkplug but no fuel is directly injected into the prechamber. Figure 40 shows a production implementation of a passive prechamber system in the Maserati "Nettuno" engine going into production in the 2021 MC20. The engine has two spark plugs, one in the main combustion chamber and the other in the prechamber. Each cylinder is equipped with a 6 bar Port Fuel Injector (PFI) and 350 bar direct injector. In this application, the system is used to enable fast combustion and knock reduction enabling a BMEP of 32 bar at a high compression ratio of 11.

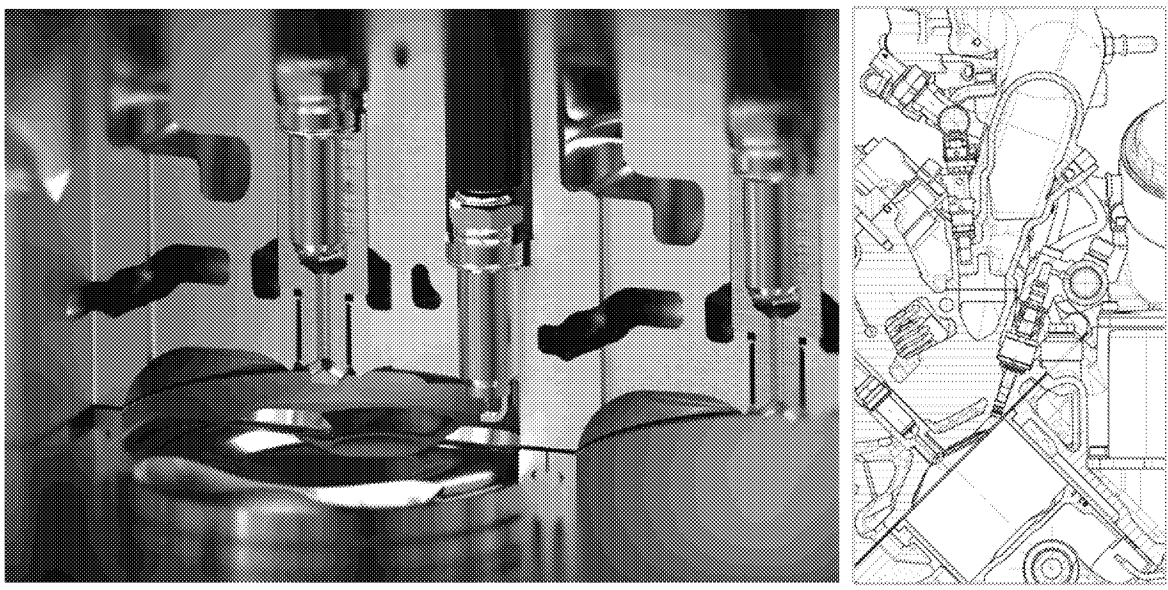


Figure 40: Maserati "Nettuno" engine combustion chamber and passive prechamber details. Source (Maserati)

- Active prechamber ignition (figure 28, center) – The prechamber has a spark plug and a small, dedicated fuel injector. This system enables a rich air-fuel mixture in the prechamber resulting in more active species in the jet that initiates combustion in the main chamber. Active prechamber systems can ignite more dilute mixtures when compared to passive systems. Figure 41 [59] shows Ricardo's latest results (Feb 2021) from the Magma xEV dedicated engine for hybrids. The prechamber (active) ignition system achieved a 47% Brake Thermal Efficiency (BTE) at λ~2.2 and 45% BTE (passive) at λ=1.6 respectively. The passive prechamber spark plug was also capable of 41% BTE at λ=1 with cEGR.
- Scavenged prechamber ignition (figure 28, right) – has a system to introduce fresh air to purge the burnt gases from the prechamber. This system further expands the limits of the prechamber system at the cost of the added complexity of the cylinder head [60]. Study [60] showed that the engine could operate (with COV IMEP <2%) at λ=1 with an EGR dilution of 40%. The system also enabled lean operation at λ>2. A possible approach to simplify a scavenged active prechamber would be to use an air-assisted fuel injector in the prechamber. Air-assisted injectors like the one pioneered by Orbital Corporation (Australia) [91,92] could make the cylinder head design for a scavenged active prechamber no more complicated than an active prechamber.

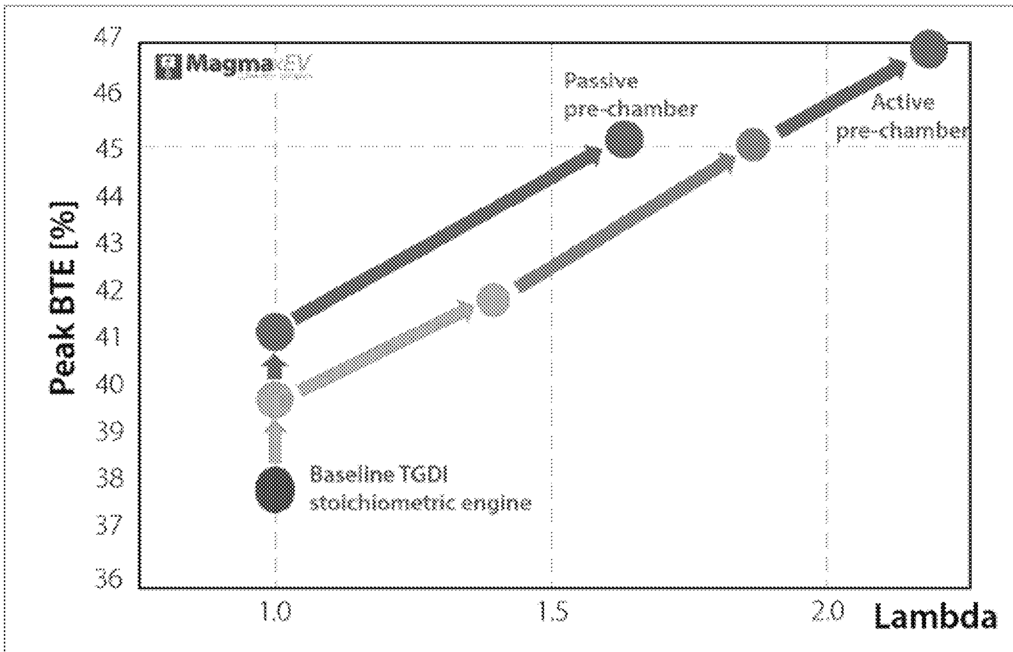


Figure 41: Lambda and efficiencies of different prechamber configurations - Ricardo Magma xEV [59]

Honda's research on an active prechamber jet ignition [62,63] system achieved an engine out NOx emission of 30 ppm and hydrocarbon emission of 2000 ppm putting it in compliance with the SULEV20 emission regulation. The engine with a geometric compression ratio of 16 achieved a high load BMEP of 8.7 bar at an AFR of 35:1 (less than 1% COV of IMEP) and a brake thermal efficiency of 47.2% while maintaining a 50% mass fraction burn timing between 6 and 8 CAD after combustion TDC.

11.5 Microwave Ignition Systems

Microwave space ignition systems developed by Microwave Ignition (MWI) AG [33] use pulsed microwaves to produce a large number of ignition sites distributed homogeneously throughout the combustion chamber [33]. After ignition, the combustion transitions to the turbulent regime, almost entirely skipping the slow laminar flame development stage when using a spark plug. This high combustion rate enables ignition after TDC resulting in more of the fuel energy being converted to work by the piston (Figure 42). The Ignition timing and fast combustion after TDC result in lower peak combustion temperatures and reduced NOx emissions compared to a conventional SI engine operating under similar mixture conditions [33]. The system can operate in the lean range of lambda from 1.5 to 3.

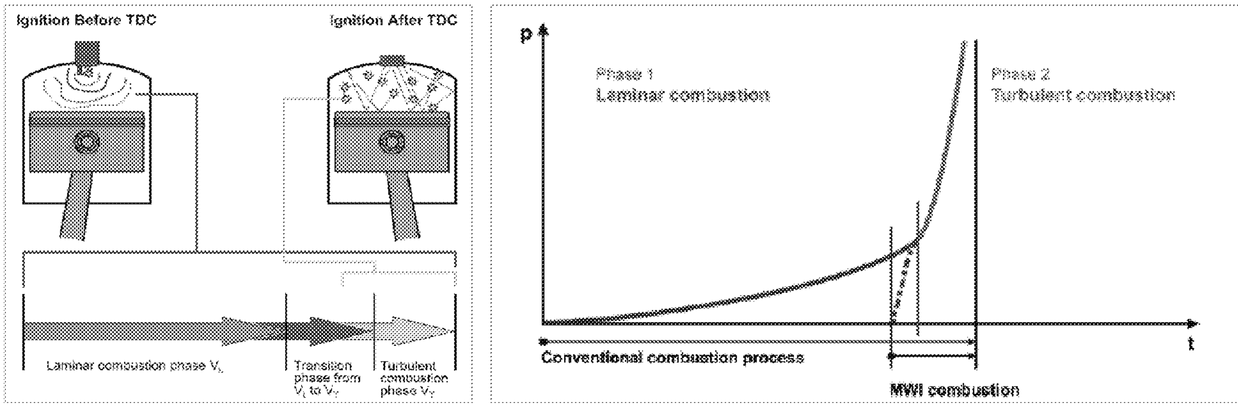


Figure 42: Benefit of microwave ignition [33]

[34] studied a microwave enhanced ignition system in which regular spark was enhanced by microwaves which increased the initial flame speed, extended lean limit, and decreased COV of IMEP. The ignitor was built to fit in place of an M12 spark plug in a production NA 3-cylinder engine without any modifications. The durability of the system was tested for the equivalent 20,000 km of highway driving without any noticeable wear or deterioration in performance. At 3.8 bar 1400 rpm, the engine was able to operate at an AFR of 30 with COV of IMEP below 5%. The exhaust gas temperature was below 300°C and the engine out NOx was less than 10 ppm.

The ability to reliably ignite lean mixtures renders mixture enrichment near the spark plug under similar in-cylinder mixture composition unnecessary. Microwave ignition has the potential to realize air diluted homogeneous lean-burn engines that operate at lambda exceeding 2, conditions under which combustion temperatures are below the NOx formation threshold negating the need for NOx aftertreatment system. Currently, such lean mixtures can only be ignited by compression ignition (HCCI, SACCI, etc.) or active prechamber ignition systems. Even at such high air dilution rates, the engine might still require an SCR system to meet the 2025 Fleet average NMOG+NOx limit of 30 mg/ mile (Tier 3 Bin 30) making them unattractive for volume production. Nevertheless, high-energy ignition systems like microwave ignition can significantly increase the EGR dilution rate, negate the requirement of mixture enrichment near the ignition source (reducing HC emissions), maintain high burn rates (ideal combustion phasing - high efficiency at low loads, reduced knocking at high loads).

12.0 Technology Summary

The baseline engine in most of the studies below is of a Turbo1 (NHTSA designation) technology level – Direct Injection, Turbocharged with dual VVT. The efficiency (peak and different rpm-BMEP points) of Turbo1 level engines from different manufacturers are different depending on the maturity of the technology at the manufacturer, other components of the powertrain (transmission, etc.), and the specific requirements of the vehicles that the engine be used in. Some of the studies do not give a specific baseline efficiency, only a percentage improvement. The efficiency of the baseline engine/ point can be assumed to be in the 35-39% range.

Technology	Baseline engine	Comments	Engine efficiency/ Emissions
Adding reformate			
DEGR	NA PFI, CR 10.5 (GM production engine)	CR raised to 14	The efficiency gain of 10% across the engine map. 42% peak efficiency
	Turbo DI, Dual VVT, CR 9.3 (GM production engine)	CR raised to 11.7	2000 rpm 2 bar - BTE improvement 14.3% Peak BTE improvement 10.2% 'Vehicle fuel economy improvement 13% and 9% over city and highway (2012 Buick Regal) NOx + NMOG < 31mg/mile (almost Tier 3 Bin 30)
Pilot fuel injection during NVO	Turbo DI, Dual VVT, CR 9.25 (GM production engine)	CR raised to 11.7 The primary aim of the study was not fuel economy improvement with in-cylinder reforming (needs study to quantify benefits)	1800 rpm 3 bar - EGR 32% BTE improvement at the operating point 22% of baseline
Catalytic EGR	Turbo DI, Dual VVT, CR 9.2 (GM production engine)	Compression ratio not increased	2000 rpm 4 bar - BTE improvement 8% over baseline. EGR tolerance 25% to 50%

High energy ignition systems			
300mJ spark plug	Turbo DI, Dual VVT, CR 12 (Nissan production engine - modified compression ratio)	Doubled EGR tolerance of the base engine. The results will be very dependent on base engine optimization for EGR diluted combustion	Compared to the baseline Spark plug, at 1200, 2000, and 3000 rpm and 3 bar, BSFC decreased by 25, 12, and 10 g/kwh respectively. Considering typical BSFC values, that is in the range of 8 to 3 %. EGR Tolerance was 29, 23, 22% respectively
Prechamber ignition systems - Passive	Turbo DI dual VVT		Peak BTE 42-45% Stoic operation EGR rate 30- 40% Lean operation $\lambda \approx 1.6$ (NOx levels feasible for NOx aftertreatment
Prechamber ignition systems - Active	Turbo DI dual VVT	Most studies CR + 2 of baseline. Some studies up to 16:1	Peak BTE 44-48% $\lambda > 2$, all studies NOx<100ppm. Some studies < 10ppm
Corona Ignition systems	Turbo DI, Dual VVT, inlet VVL, CR 12 (BMW production engine - modified compression ratio, +1)	The engine could be operated under higher EGR and air dilution	1250 rpm 3bar - EGR tolerance 44% Efficiency not reported
Microwave ignition		Ability to operate under lambda > 2 (technology further out in the future)	

13.0 Conclusions

Based on the discussions of various technologies to increase engine efficiency and technology pathways for various types of engines in the 2025-2035 period, we have the following recommendations for technologies/ projects that can demonstrate significant fuel economy benefits with currently available technologies and future technologies

13.1 Pickup Truck/ Full-Size SUV Powertrain

13.1.1 Naturally aspirated + 30kW - 48V P2 hybrid + Advanced deac

Full-size SUVs and pickup trucks use engines sized for the maximum tow rating. Under normal operation, the engine operates under light loads where the engine is throttled and has low efficiency. This is especially true for naturally aspirated engines. Such engines can benefit from advanced deac whose benefits are currently limited by driveline torsional vibrations, NVH, and durability concerns. Integrating a high-power 48 Volt P2 mild hybrid system (30kW) into such a vehicle using it to actively smooth out torque pulsations will enable more aggressive deac strategies and higher fuel economy benefits.

Such a system will also have the following additional benefits

- Start-stop
- Electric creep
- Regen braking
- Slow speed electric drive
- Heated catalyst (enabled aggressive start to stop)

Depending on system integration factors Roush estimates a fuel economy improvement exceeding 20% on a baseline naturally aspirated Direct Injection V8 with variable valve timing.

The study can also investigate the potential benefits/ feasibility of changing the base engine architecture

- Lower bore to stroke ratio engine design
- Atkinson cycle, EGR dilution, and high energy ignition systems that can reduce burn duration of dilute mixtures

13.1.2 Future Powertrain

Conduct a study to evaluate the fuel economy limits of an IC engine powered light-duty pickup truck by using a powertrain with the following technologies

- Turbocharged low bore to stroke ratio Miller cycle engine with an active prechamber ignition system and lean burn with $\lambda>2$
- Electric assisted turbocharger or turbo + electric supercharger – enable turbine upsizing and control of residuals and increasing knock resistance and enabling higher compression ratio

- Hybrid power train sized to give a limited range in electric mode
- All-electric accessories (HVAC, coolant pumps, etc.)

Studies have shown that lean burn active prechamber systems can attain an engine BTE of 45-50% (section 9.4). The hybrid system will enable the IC engine to be optimized for operation in a narrow speed load range.

13.2 The benefit of a high power 48-volt system + advanced boosting system on a compact SUV

The study will quantify the fuel economy benefit of A 30kW 48-volt P2 system mated to a low bore-to-stroke ratio miller cycle engine with an electrified boosting system, advanced cylinder deactivation, cooled EGR and a heated catalyst. The compact SUV is one of the largest segments in the US market. A 30kW 48-volt P2 system can provide near-full hybrid functionality in such a vehicle at lower cost. The 48V electric motor can supplement the engine torque under low-speed high load conditions, thereby avoiding this knock-prone area of the engine map. Using an advanced boosting system - turbocharger + 48V electric supercharger will reduce engine backpressure (larger turbine) and improve scavenging, reduce residuals, reducing knock. A combination of a high-energy ignition system (high energy spark plug/ plasma ignition) and fuel reforming by pilot fuel injection during NVO can be used to increase cEGR tolerance at low loads.

This will enable the use of a higher compression ratio, increasing efficiency. Part of this project might involve engine testing and part modeling if certain aspects of building a prototype system are too difficult. The fuel economy improvement will be dependent on the level of optimization of engine design, calibration, and turbocharger selection. Rough estimates a fuel economy gain above 30% compared to a level 1 (NHTSA) turbocharged engine.

13.3 Effect of NVO fuel reforming on EGR tolerance on an engine

Adding small amounts of hydrogen (or H2 and CO-rich reformate produced from gasoline) to the in-cylinder charge can significantly enhance combustion stability, burn rates and EGR tolerance. In-cylinder fuel reforming by using pilot fuel injection during NVO (Section 7.2) has shown the ability to significantly improve cEGR tolerance, combustion stability, and engine efficiency. Such a system can have wide application in turbocharged and NA engines across different vehicle segments. Also, the hardware requirements of such a system are minimal (Properly chosen cam profiles and VVT mechanism with the control authority for sufficient NVO).

Study the effect of NVO fuel reforming on the dilution tolerance of an HCR engine like the Toyota A25A-FKS and/or on a turbocharged engine designed for cooled EGR.

Optional topics of study

- Study benefit of NVO fuel reforming on startup emissions, combustion stability during retarded combustion for catalyst warmup

- Study combination of NVO reforming and high energy spark plug/ prototype corona ignition systems on dilution tolerance

Depending on the base engine, Roush estimates an efficiency improvement in the range of 5 to 10%.

13.4 Benchmarking a production passive prechamber engine for knock resistance and EGR tolerance

Prechamber combustion systems (section 8.4) are one of the most promising technologies for improving the dilution limit of engines (lean burn and cEGR diluted stoichiometric) thus increasing engine efficiency across different vehicle segments. It can also enable extremely fast burn rates increasing the knock tolerance of turbocharged engines.

The Maserati Nettuno engine in the 2021 Maserati MC20 will be the first application of a passive prechamber engine in production. Though this is a high-performance engine with a peak BMEP exceeding 30bar (according to Maserati press materials), it will be valuable to study the effect of the system on knock tolerance, burn rates, and dilution tolerance (EGR and air), and emissions. Alternatively, a production engine could be modified with a passive prechamber.

Both approaches are suboptimal since ideally the design of the cylinder head, the combustion chamber, and the prechamber, position of the fuel injector, number of spark plugs (will the main chamber have a second spark plug?) will all have to be optimized for maximizing the engine for cEGR dilution and BTE. This would require significant CFD and experimental work that feeds into each other.

Areas of study

- Knock tolerance
- EGR and air dilution limits and efficiency improvement
- Studying the engine-out NOx emissions during lean-burn (air diluted) and assessing the attractiveness of EGR diluted stoichiometric + TWC vs air diluted lean + NOx aftertreatment system.
- Combining the passive prechamber system with some form of fuel reforming to assess if the lean (air diluted) operation limit at low loads can be extended to a lambda value where no NOx aftertreatment is required.

The effort will be focused on quantifying possible efficiency gains in a non-performance application.

13.5 Evaluate/ support research on production intent high energy ignition systems that can replace a spark plug

High energy volume ignition systems can enable combustion of dilute (cEGR/ air) in cylinder mixtures resulting in a step-change in engine efficiency of both turbocharged and naturally aspirated engines. These technologies can enable dilute stoichiometric operation (cEGR dilution) in large-bore engines, something that is very difficult with spark plugs. Prototypes of technologies like Microwave volume ignition have shown the ability to operate at lambda >2 which can result in lean-burn engines with peak temperatures below the NOx formation threshold negating the need for NOx after-treatment systems

Such systems can be a drop-in replacement for a spark plug without any major change engine architecture making them very attractive. Hence there is value in supporting near-production high energy ignition technologies so that the advantage of such systems is documented, and issues can be identified and resolved accelerating their timeline to production.

Roush estimates that systems like plasma ignition systems with high amounts of cooled EGR can have an engine efficiency improvement in the range of 5-10% on a baseline turbocharged DI, dual VVT engine. Microwave ignition can potentially compete with prechamber ignition systems enabling lean-burn engines with low engine-out NOx emissions with BTE exceeding 45%.

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